PROCEEDINGS OF SCIENCE

Simulation study of the detected and expected events for the EUSO-TA fluorescence detector

F. Bisconti[a], F. Catalano[b], F. Fenu[b,c], M. E. Bertaina[b,c], T. C. Paul[*d] and H. Shin[e]
for the JEM-EUSO Collaboration
[a] *Karlsruher Institut für Technologie, Germany*
[b] *Università degli studi di Torino, Italy*
[c] *Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy*
[d] *Lehman College, City University of New York, USA*
[e] *Institute for Cosmic Ray Research, University of Tokyo, Japan*
E-mail: francesca.bisconti@kit.edu

EUSO-TA is a ground-based cosmic ray fluorescence detector, pathfinder of the JEM-EUSO experiment, installed in 2013 at the Telescope Array (TA) site, in front of a TA fluorescence detector station at the Black Rock Mesa site (TA-FD), and completed with the focal surface detector in 2015, when it started to be operational. The data acquisition works in coincidence with TA. This guarantees an easy identification of the cosmic ray events detected by EUSO-TA with reliability of the TA-FD event detection and reconstruction methods. Up to now, a few cosmic ray events have been identified. Two simulation software are developed for the JEM-EUSO detectors: ESAF and Offline. ESAF is the software package that has been developed in the efforts of the EUSO and JEM-EUSO projects; Offline was originally developed and successfully tested for years by the Auger Collaboration, and it has recently been adapted for the JEM-EUSO detectors. Thanks to the first events detected by EUSO-TA, ESAF and Offline have been improved in order to have a good comparison between data and simulations. This made the evaluation of the EUSO-TA detection threshold possible, with an Offline study based on the simulated air showers according to TA reconstruction. In parallel, an independent simulation to estimate the number of detectable events by EUSO-TA has been conducted using ESAF code. The simulation methods are described in this work, as well as the comparison between the number of actual detected events and the number of expected ones.

35th International Cosmic Ray Conference - ICRC2017
10-20 July, 2017
Bexco, Busan, Korea

*Speaker.

1. Introduction

The EUSO-TA experiment, discussed more in detail in these proceedings [1], is a pathfinder detector of the JEM-EUSO project [2]. The aim of JEM-EUSO is to detect the rare Ultra-High Energy Cosmic Rays (UHECRs), with energy $\sim 10^{19}$ eV and flux ~ 1 particle km^{-2} century^{-1}, from space, on board the International Space Station. Observing the UV fluorescence light emitted by cosmic ray extensive air showers through the atmosphere, which is used as a vast calorimeter, the probability to detect UHECRs is largely increased, with an observation area projected on ground of up to $\sim 10^5$ km^2, much larger than that of experiments on ground.

The purpose of the EUSO-TA experiment is to validate the observation principle and the design of JEM-EUSO detecting air showers on ground. Indeed, it is located at the Telescope Array (TA) [3] site in Utah (USA), in front of the Black Rock Mesa fluorescence detectors (TA-FDs) station [4]. The location of EUSO-TA is strategic. First, it is possible to detect air showers in coincidence with TA-FD; second, the available Electron Light Source (ELS) [5] and the Central Laser Facility (CLF) [6] can be used to test and calibrate the detector.

2. EUSO-TA detector

2.1 Design

EUSO-TA is a down-scaled version of JEM-EUSO. The optical system consists of two flat squared Fresnel lenses of side 1 m with 8 mm thickness [7]. The optical system allows to EUSO-TA a field of view (FOV) of $\sim 11°$.

The EUSO-TA focal surface has a concave shape. It is made of one Photo Detector Module (PDM), which is a nominal 17 cm $\times$ 17 cm area composed by an array of 6×6 Hamamatsu Multi-Anode PhotoMultiplier Tubes (MAPMTs). Each MAPMT is a matrix of 8×8 pixels side 2.88 mm for a total of 2304 pixels over the whole PDM. 2×2 MAPMTs make a unit called Elementary Cell (EC). A UV transmitting band pass filter in the range $290 - 430$ nm is glued on top. Each pixel has a gain (electron multiplication ratio) of more than 10^6 which allows single photon counting. The total photon detection efficiency of the MAPMTs has a maximum of 25%.

2.2 Operation

Like all fluorescence cosmic ray detectors, EUSO-TA works in night time and best in clear sky conditions, to reduce effects of atmospheric and cloud attenuation. The instrument is pointed with an elevation manually adjustable between 0° and 25° respect to the horizontal direction, whereas the azimuth is fixed at 53° from North counterclockwise, pointing to the CLF.

As anticipated, there is the possibility to acquire data in coincidence with TA-FDs as *external trigger*: in case of a trigger signal received by TA-FDs, a packet of 128 data frames centered around the TA-FDs trigger is saved, which otherwise would be overwritten. A data frame contains the number of counts per pixel integrated over 2.5 μs (called Gate Time Unit (GTU)). A GTU represents the time resolution of the EUSO detectors. It has been designed for the data acquisition of air showers from space, corresponding to the time needed by light to cross a JEM-EUSO pixel. This acquisition mode allows one to know in advance if EUSO-TA could have detected showers, thanks to the large FOV of TA-FDs which encompasses the EUSO-TA one. Moreover, from the shower reconstruction made by the TA experiment, the nature of the event (i.e. arrival direction, core position and energy) would be then known and used for further analysis. However, since the area of the sky observed by TA-FDs is about 30 times the one observed by EUSO-TA, the amount of data saved is larger than the actual data containing events, that makes the research of events more challenging.

Another acquisition mode consists in using an *internal trigger*, also called *first level trigger* (L1) [8], implemented for the JEM-EUSO experiment. The L1 principle consists of counting an excess of signals over background in groups of 3×3 pixels lasting more than a preset time. The internal trigger has been tested, but the current electronic system allows the implementation of the trigger logic only for a few ECs. For this reason, most of the data have been acquired with the external trigger.

In the year 2015 four data acquisition campaigns were done in coincidence with TA-FDs, and one in 2016, for a total of about 140 hours (120 hours in 2015, to which this work refers). Up to now four events are considered surely detected. Two of them are related to nearby landing showers, lasting 1 GTU, while the other two are farther and last 2 and 3 GTUs. Moreover, four additional events are considered as candidate events, because they are faint or exhibit an irregular track.

3. ESAF and Offline frameworks

The EUSO Simulation and Analysis Framework (ESAF) described in [9] and the Offline framework described in these proceedings [10] are the two software packages used for the showers simulation and reconstruction in the JEM-EUSO project and its pathfinders. The two frameworks have been developed independently and analysis results can be cross checked. Both perform the simulation of the shower development in the atmosphere originating from an input primary cosmic ray, emission and propagation of the photons from the shower to the detector and detector simulations such as optical ray trace and electronics response. Furthermore, algorithms and tools for the reconstruction of the shower properties are included. They are written in C++ in a modular way, each module performing a different step of the simulation. Both fluorescence and Cherenkov light production are taken into account as well as the ground reflected and scattered light.

ESAF has been developed in the framework of the ESA-EUSO mission [11]. Several shower simulators are implemented in ESAF, following parametrical and Monte Carlo approach. As parametrical generator, the Gaisser-Ilina-Linsley (GIL) function [12], is used to reproduce the profile as function of energy and slant depth. Other generators such as the Monte Carlo simulator CORSIKA [13] and CONEX [14] are interfaced with ESAF. Physical processes are divided into class modules that are strongly connected with each other.

The initial implementation of Offline [15] began in 2003 for shower simulation and reconstruction, and analysis of fluorescence and surface detector data of the Pierre Auger Observatory [16]. In March 2013 the adaptation of Offline was started to carry out simulations of JEM-EUSO, as well as its pathfinders. The Offline framework takes input shower profiles simulated with the most popular air shower simulation packages, i.e. CORSIKA, CONEX, AIRES [17] and SENECA [18]. Simulation and reconstruction tasks are performed by algorithms contained in modules run in sequence. This modular design facilitates comparison of algorithms and building a variety of applications by combining modules in various sequences. The user can provide instructions via configuration files written in an XML-based language. This approach has proven to be sufficiently flexible and simple to use.

4. Simulation of the detected events with Offline

Improvements regarding the telescope and electronics simulators have been recently made in Offline in order to reach a better matching of the simulations with data. Figure 1 shows one of the

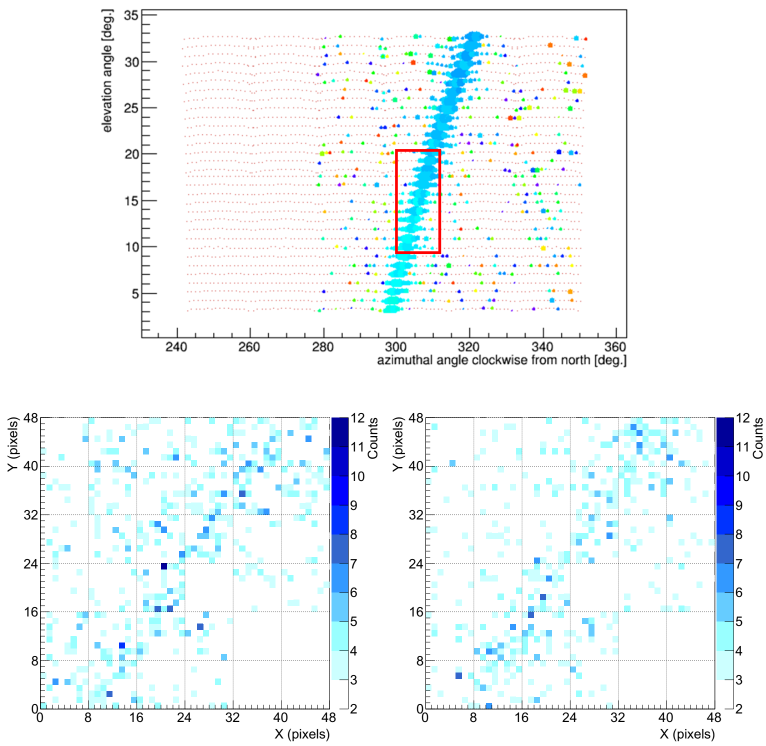

Figure 1: *Top*: TA-FDs event with EUSO-TA FOV overlapped (red rectangle). The marker size is proportional to the number of photons coming from a certain direction and the color corresponds to the arrival time of the photons (violet means earlier, red means later). The signal is integrated within a 51.2 μs time window. Image by courtesy of the TA collaboration. *Bottom-left*: the same event detected by EUSO-TA, within a 2.5 μs time window. *Bottom-right*: the corresponding simulated event.

detected events, with impact parameter $R_p = 2.5$ km and 10^{18} eV, lasting 1 GTU. The top panel shows the event as detected by TA-FDs in the frame elevation and azimuth, with the EUSO-TA FOV indicated by the red rectangle. Each circle represents one PMT of the TA-FDs. One can see that the spatial resolution is higher for EUSO-TA than that for TA-FDs, while the area of the sky observed is smaller for the first than for the latter. The bottom-left panel shows the detected event and the bottom-right panel the simulated one; both frames show the number of counts per pixel on the full PDM over a time window of 2.5 μs. The simulated event is added onto the background taken by data in the same packet but extrapolated from a few μs before or after the events. The total signal from the simulated event has $\sim$800 counts. Data and simulation are in good agreement from a visual point of view: counts, orientation and width of the tracks look similar.

Given the good agreement between data and simulations, we made a systematic study to estimate the detection threshold of EUSO-TA. Thanks to TA, we are aware of which showers crossed the EUSO-TA FOV, independent from whether the event is actually distinguishable in the EUSO-TA data or not; of these showers, the reconstruction parameters were provided to us, i.e. the arrival direction, the energy, the core position on ground and the event time. The top panel in Figure 2

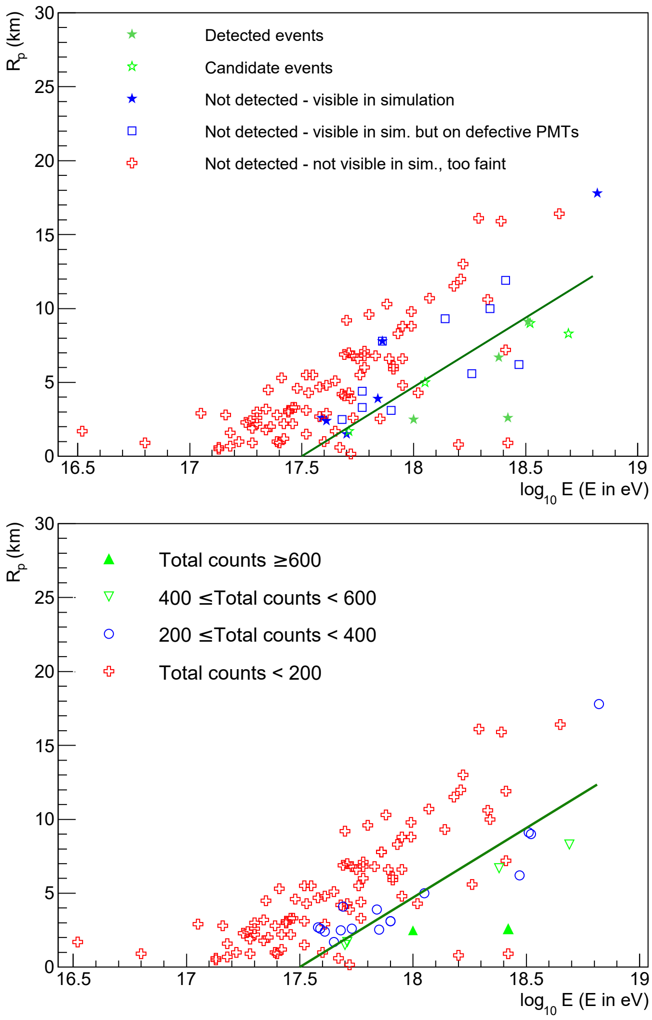

Figure 2: Events which crossed the EUSO-TA FOV during the data acquisitions in 2015. *Top*: Detected and candidate events, lying under the green line, and not detected events. *Bottom*: The same events considering the number of total counts originating the simulated events.

represents a total of 110 showers with their impact parameter R_p and their energy E which crossed the EUSO-TA FOV during the acquisition campaigns in 2015. Among those events, four were detected by EUSO-TA along with four more candidate events, all lying in the area of the plot under the green line.

Given the parameters of the air showers, we simulated these events with the purpose of understanding what makes a shower detectable or not. From this study, five events were visible in the simulation, but no counterparts in the data were identified; ten events hit defective MAPMTs and thus cannot be detected; all the other events were too faint to be visible over background.

From the simulations we retrieved the total number of counts per event, summing up the counts over the GTUs in which the signal was distributed and not considering the background. The bottom panel in Figure 2 displays the result in four sets of total counts. The overall result is that 23 simulated events have more than 200 counts, of which six (almost all the detected and candidate events) have more than 400 counts and two have more than 600 counts. This defines the detection threshold of EUSO-TA. We have to consider the high variability of the background, which might hide the events. Moreover, the total counts considered here refer to the sum of counts from the event track crossing the whole PDF over one or more GTUs. Acquiring data with the internal trigger, which looks recursively to small portion of the PDM, the counts necessary to get a trigger would be higher than those with the external trigger, used to collect the analyzed data. All these factors introduce fluctuations on the detection threshold. Therefore, we consider a flexible threshold of 600 counts. However, in fortunate conditions with low background rate and with external trigger, also events with lower counts can be detected. For comparison, the night sky background varies between $1-1.8$ counts per pixel per GTU, corresponding to $60-115$ counts on one MAPMT. Considering the threshold of 600 counts for a detectable event and assuming that on average a shower track crossing the EUSO-TA FOV hits 6 MAPMTs, a signal of $\sim$100 counts from the shower on one MAPMT is necessary to have an event distinguishable from the background.

5. Evaluation of the number of expected events with ESAF

The total number of detected events in coincidence with TA-FD is four, to which the four candidate events can be added. We tried to estimate if this number is reasonable compared to the expectations that we would get from simulations. For this purpose ESAF was used, since it has been already used in the past to estimate the performance of JEM-EUSO and its pathfinders.

In this analysis we assumed a TA-FDs trigger efficiency of 100% and an EUSO-TA pixel mean efficiency of 10%. The number of expected events N_{exp} is then obtained as:

$$N_{exp} = A_{sim}\Omega_{sim}T f_{FOV} \int_{10^{17}(eV)}^{10^{19}(eV)} \frac{N_{sel}(E_0)}{N_{sim}(E_0)} J(E_0)dE_0 \tag{5.1}$$

where $A_{sim} = \pi R_{max}^2$ is the simulated area up to the radius $R_{max} = 50$ km from the EUSO-TA detector, $\Omega_{sim} = \int_0^{2\pi}\int_0^{\pi/2} \sin\theta\cos\theta d\theta d\varphi$ is the simulated solid angle acceptance and $T = 120$ hours is the considered acquisition time, which corresponds to the actual total acquisition time in the year 2015. f_{FOV} is the fraction of showers that enter the EUSO-TA FOV and have an impact parameter between 1 and 10 km. $N_{sel}(E_0)$ is the number of selected showers with counts above 200, 400 or 600 (integrated over 3 consecutive GTUs) among $N_{sim}(E_0)$ simulated showers with an energy between E_0 and $E_0 + dE_0$; we simulated 1000 showers within the EUSO-TA FOV with $\Delta N_{sim}/\Delta E_0 \propto E^{-1}$ to increase the statistics of higher energy showers. Of these events, 229 have total counts higher than 200 counts, of which 118 events have more than 400 counts and 67 events have more than 600 counts. These events are shown in Figure 3. $J(E_0)$ is the assumed cosmic ray flux modeled with experimental measurements. The cosmic ray flux $J(E_0)$ in the range $10^{17} - 5\times10^{17}$ eV has been taken from IceTop measurements [19] and in the range $5\times10^{17} - 10^{19}$ eV has been taken from Auger measurements [20]. The result indicates that EUSO-TA could have detected 6 events with the detection threshold of 600 counts, which is in the range of the counts excess obtained in

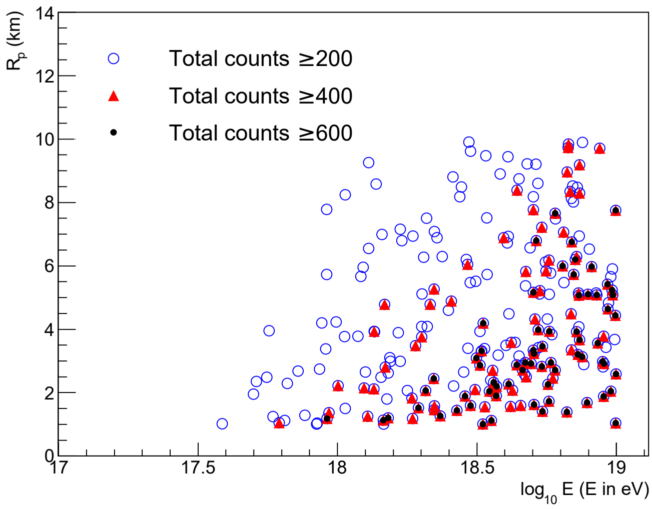

Figure 3: Events expected in the EUSO-TA FOV with total counts higher than 200, 400 and 600, respectively 229, 118 and 67 events out of 1000 simulated events. Here, a cosmic ray power spectrum with slope E^{-1} has been considered, that leads to more events at the high energies than with the actual slope of about E^{-3}.

Section 4. Reducing the threshold 22 events could be detected with more than 400 counts and 108 events with more than 200 counts. This result confirms, at first order of approximation, the capability of ESAF to reproduce the air showers detected by EUSO-TA and that the number of collected events is in the range of the expectations.

6. Conclusion

We performed analysis of the events detected and detectable by EUSO-TA with the ESAF and the Offline frameworks. The results in terms of detection threshold of the detector and the number of detectable events are, in first approximation, in agreement. There is a slight difference between the expected and the actual number of showers which crossed the EUSO-TA FOV. The discrepancy decreases with the increase of the signal threshold. This could be due to the fact that just the events detected by TA have been simulated with Offline, while with ESAF more generic distributions for the energy and the impact parameter have been assumed, which might lead to more events, as well as the assumed TA-FD trigger efficiency and the EUSO-TA pixel efficiency which could be lower. Another factor which may affect the number of actually detected events is the background variation, that may hide tracks of distant or low energy showers, i.e. faint events. This could contribute to the lack of detected events, especially those with low counts.

Acknowledgments

The support received by TA collaboration is deeply acknowledged. This work was partially supported by Basic Science Interdisciplinary Research Projects of RIKEN and JSPS KAKENHI Grant (22340063, 23340081, and 24244042), by the Italian Ministry of Foreign Affairs and International Cooperation, by the "Helmholtz Alliance for Astroparticle Physics HAP" funded by the Initiative and Networking Fund of the Helmholtz Association, Germany, by NASA award 11-APRA-0058 in the USA, and by Slovak Academy of Sciences MVTS JEM-EUSO as well as VEGA grant agency project 2/0076/13. Russia is supported by the Russian Foundation for Basic Research Grant No 13-02-12175-ofi-m. The Spanish Consortium involved in the JEM-EUSO Space Mission is funded by MICINN & MINECO under the Space Program projects: AYA2009-06037-E/AYA, AYA-ESP2010-19082, AYA-ESP2011-29489-C03, AYA-ESP2012-39115-C03, AYA-ESP2013-47816-C4, MINECO/FEDER-UNAH13-4E-2741, CSD2009-00064 (Consolider MULTIDARK) and by Comunidad de Madrid (CAM) under projects S2009/ESP-1496 & S2013/ICE-2822.

References

[1] L. W. Piotrowski et al. (JEM-EUSO Coll.), "The EUSO-TA detector: status and performance", Proc. of the ICRC2017 (2017)

[2] J.H. Adams Jr. et al. (JEM-EUSO Coll.), "JEM-EUSO observational technique and exposure", Astropart. Phys., vol. 40, pp. 117 – 134 (2014)

[3] M. Fukushima et al., "Telescope Array project for extremely high energy cosmic rays", Prog. Theor. Phys. Suppl., no. 151, pp. 206 – 210 (2003)

[4] H. Tokuno et al., "New air fluorescence detectors employed in the telescope array experiment", Nucl. Instr. & Meth. A, vol. 676, pp. 54 – 65 (2012)

[5] T. Shibata et al. (Telescope Array Coll.), "Absolute energy calibration of the Telescope Array fluorescence detector with an Electron Linear Accelerator", Proc. of the ICRC2011, vol. 3, pp. 309 – 312 (2011)

[6] S. Udo et al., "The Central Laser Facility at the Telescope Array", Proc. of the ICRC2002, vol. 5, pp.1021 – 1024 (2002)

[7] Y. Hachisu et al., "Manufacturing of the TA-EUSO and the EUSO-Balloon lenses", Proc. of the ICRC2013 (2013)

[8] M. Bertaina et al. (JEM-EUSO Coll.), "The first level trigger of JEM-EUSO: concept and tests", Nucl. Instr. & Meth. in Phys. A, vol. 824, pp. 253 – 255 (2016)

[9] F. Fenu et al., "The ESAF simulation framework for the JEM-EUSO mission", Proc. of the ICRC2011, vol. 3, pp. 116 – 119 (2011)

[10] T. C. Paul et al. (JEM-EUSO Coll.), "New simulation and reconstruction software for the EUSO pathfinders, with example applications", Proc. of the ICRC2017 (2017)

[11] L. Scarsi et al., "ESA-EUSO Report of the Phase A Study", http://euso.iasf-palermo.inaf.it/

[12] N. P. Ilina et al., "Cherenkov radiation and parameters of extensive air showers", Sov. J. Nucl. Phys. vol. 55, pp. 1540 – 1547 (1992)

[13] D. Heck et al., "CORSIKA: a Montecarlo code to simulate Extensive Air Showers", Report Forshungszentrum Karlsruhe (1998)

[14] T. Bergmann et al., "One-dimensional Hybrid Approach to Extensive Air Shower Simulation", Astropart. Phys., vol. 26, pp. 420 – 432 (2007)

[15] S. Argirò et al., "The Offline Software Framework of the Pierre Auger Observatory", Nucl. Instr. & Meth. in Phys. Res. A, vol. 580, pp. 1485 – 1496 (2007)

[16] A. Aab et al., "The Pierre Auger Cosmic Ray Observatory", Instr. and Meth. for Astroph. A, vol. 798, pp. 172 – 213 (2015)

[17] S. J. Sciutto, "AIRES: A System for air shower simulations (Version 2.2.0)" User's guide and reference manual (1999)

[18] H. J. Drescher et al., "Air shower simulations in a hybrid approach using cascade equations", Phys. Rev. D 67, 116001 (2003)

[19] B. Ruzybayev et al. (IceCube Coll.), "Measurement of the Cosmic Ray Energy Spectrum with IceTop 73", Proc. of the ICRC2013 (2013)

[20] A. Schulz et al. (Pierre Auger Coll.), "The measurement of the energy spectrum of cosmic rays above 3×10^{17} eV with the Pierre Auger Observatory", Proc. of the ICRC2013 (2013)