EPJ Web of Conferences **283**, 06001 (2023) https://doi.org/10.1051/epjconf/202328306001
UHECR 2022

AugerPrime status and prospects

Corinne Berat[1],* *on behalf of the* Pierre Auger Collaboration[2],**

[1]Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France
[2]Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
Full author list: https://www.auger.org/archive/authors_2022_10.html

Abstract. The Pierre Auger Collaboration started a few years ago the AugerPrime project to increase the Surface Detector (SD) performance of the Pierre Auger Observatory. It aims to address the still open questions on the origin and composition of the highest energy cosmic rays by allowing a better identification of the nature of the primaries. The key element of this major upgrade is the capability of measuring the different components of extensive air showers, which will be significantly improved by the addition of a Surface Scintillator Detector (SSD) on each water-Cherenkov detector (WCD) constituting the SD. Moreover, the dynamic range of measurement is extended through an additional small photomultiplier tube inside the WCD. New electronics is processing the signals from the WCD and the SSD with higher sampling frequency and enhanced resolution. The scintillator module deployment started in 2019, and the new electronics in December 2020. The collected data allow for the evaluation of the first performances of the upgraded array and to adapt the whole data acquisition chain necessary for an efficient and sustainable operation of the Observatory. After the recall of the motivations for the upgrade, the main characteristics of the new detection setup are reviewed, as well as the status of its deployment and commissioning. The expected prospects are also discussed.

1 Introduction

The Pierre Auger Observatory [1] is the largest cosmic ray observatory, measuring extensive air showers (EAS) produced by very high-energy astroparticles that penetrate the Earth's atmosphere. It was designed to be a hybrid detector: it comprises a Fluorescence Detector (FD) and a Surface Detector (SD). The SD consists in 1600 water-Cherenkov detectors (WCD) distributed over 3000 km^2 on a triangular grid with a regular spacing of 1.5 km. It also includes two denser arrays with reduced spacing: 61 additional SD stations are deployed over 27.5 km^2 with a 750 m spacing, and 1.95 km^2 with a 433 m spacing. In each WCD, filled with ultra pure water, the Cherenkov light produced by EAS particles is viewed by three 9-inch photomultipliers (PMT). To provide a common reference for calibrating signals between all the WCD of the SD, the recorded signals are measured in units of the signal produced by a vertical muon traversing the tank, a vertical equivalent muon (VEM). The conversion of signal from hardware units to VEM is obtained by a local and automatic calibration procedure [2].

The FD is composed by 24 optical telescopes installed in 4 buildings, and overlooking the SD array, having a field of view of 30° in elevation with a minimum of 1.5° above the horizon, plus 3 additional ones, overlooking the denser arrays, with an elevation between 30 – 60° measuring lower energy air showers. To operate the FD, detailed knowledge of the atmospheric conditions is mandatory, therefore measurement and monitoring devices are installed at various locations. In the denser sub-arrays, two Engineering arrays are deployed, one to operate radio antennas (AERA[1]) [3], and the other to operate buried muon detectors (AMIGA[2]) [4].

With ~17 years of data taking during Phase I, the Observatory has accumulated high quality data, and the largest exposure to Ultra-High Energy Cosmic Rays (UHECR) reaching 90000 km^2 sr yr for spectrum reconstruction, and 122000 km^2 sr yr for anisotropy studies. This has led to a wealth of results providing major advances in our understanding of these highly energetic astroparticles, and notable results concern the energy spectrum [5], the flux composition [6], the searches for neutral particles and multi-messengers astrophysics [7] [8]. Nevertheless, several questions are still open: what are the origins of the spectrum index changes and the suppression observed at very high energy? What is the UHECR flux composition at the highest energies? Thanks to the searches for anisotropies in UHECR arrival directions, the extra-galactic origin of these particles has been proved by the observation of a dipole [9] above $\simeq$ 8 EeV. Strong hints of correlation between UHECR arrival directions and the massive, star-forming, or active galaxies positions within 200 Mpc have been obtained above 40 EeV in intermediate scale anisotropy studies [10]. However, the UHECR sources remain unknown, even if candidates are suspected. Understanding the spectrum features and measuring the

---

*e-mail: berat@lpsc.in2p3.fr
**e-mail: spokespersons@auger.org

[1] Auger Engineering Radio Array
[2] Auger Muons and Infill for the Ground Array

https://doi.org/10.1051/epjconf/202328306001

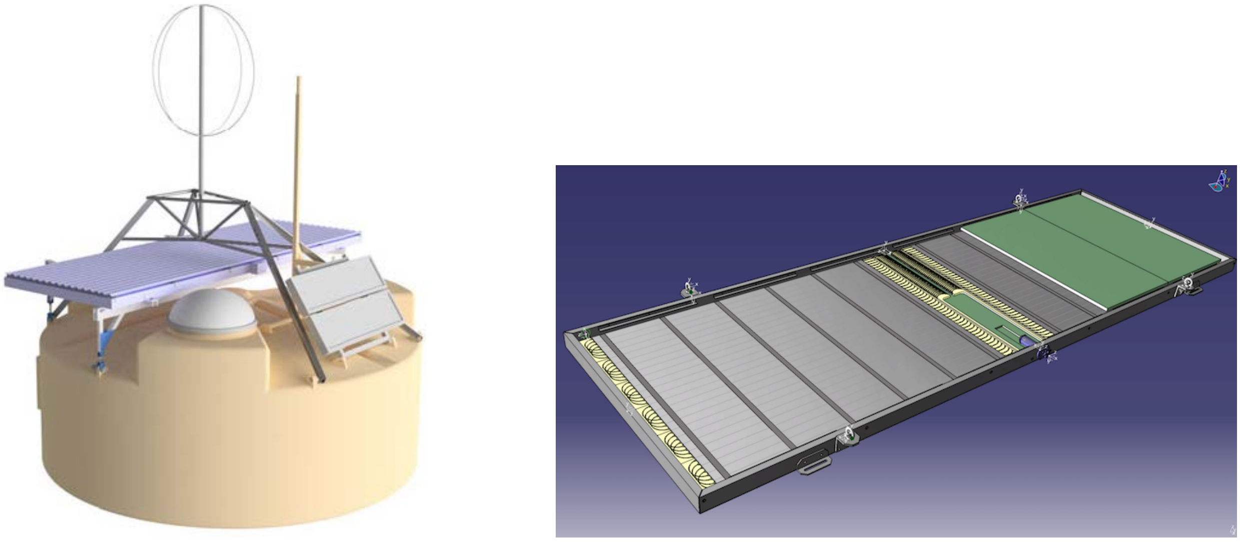

Figure 1. Left: drawing of a complete detection station for AugerPrime, with, on the WCD, a SSD module and an antenna. Right: design of one SSD module.

composition on the full energy range could constrain the source characteristics [11]. We are eager to do mass driven anisotropy studies, with the opportunity, in the case of a substantial light component of the flux, to do astronomy using these light nuclei. The various EAS measurements carried out have revealed inconsistencies between the muon content of the showers predicted by the models and that actually measured in the data (see e.g. [12] and references therein). This issue should be addressed by studying hadronic interactions in the kinematic region beyond man-made accelerators reaches.

Based on these findings, the objective of the Observatory upgrade, undertaken by the Pierre Auger collaboration and dubbed *AugerPrime*, is to measure the composition of the cosmic-ray flux at the highest energies, and to obtain an event-by-event composition. The aim is also to enhance the sensitivity to the γ and ν fluxes exploring the potential of future experiments. The upgrade should provide a unique opportunity to study EAS, hadronic interactions and multiparticle production above a 70 TeV centre-of-mass energy, to explore particle physics beyond human accelerators and thus improve constraints on new physics phenomena.

2 AugerPrime components

To study the origin of UHECRs, it is necessary to improve the knowledge of the composition of the flux at high energy and on an event-by-event basis. Currently, determinations of the cosmic-ray mass composition are obtained by direct observations with the FD of X_{max}, the slant depth of the maximum of the shower development, and indirectly by measuring observables related to X_{max} obtained with SD data. Due to the FD operating time, X_{max} direct measurements can be performed with a duty cycle of only 13% to 15%. Adding mass sensitivity to the SD is thus the key for the upgrade.

As the number of muons present in the shower is strongly correlated with the mass of the primary, it is a valuable indicator for determining the composition. Therefore, disentangling the muonic and electromagnetic components of the EAS at ground provides the required improvement towards the mentioned science goals. This can be achieved either with a muon detector or with a detector having a different sensitivity to both EAS components. The WCD is significantly more sensitive to muons, thus we need to complement the information, delivered by the WCD with other detectors more sensitive to the electromagnetic part of the shower. For AugerPrime, plastic scintillators are installed on each WCD. These surface scintillator detectors (SSD) being mostly sensitive to vertical showers, radio antennas are installed on each WCD to improve the measurements of inclined ones, via the detection of their radio emission in the 30−80 MHz frequency range (Fig. 1, left). To increase the dynamic range of the delivered signals, a small photomultiplier tube (SPMT) is added in the WCD to register large signals near the shower core impact point (the 9-inch PMTs are then named large PMTs (LPMT)). Direct measurements of the shower muon content will be performed for lower energy showers using muon detectors, consisting in scintillators buried in the denser array. To process signals delivered by existing and new detectors, new surface detector electronics is required, with higher performances than the current one. In the following are described the SSD, the SPMT, and the electronics Upgraded Unified Board (UUB). Details concerning the radio detector (RD) and the underground muon detector (UMD) can be found in these proceedings [13] [14].

2.1 Surface Scintillator Detector

A SSD unit (Fig. 1, right) consists of a box of 3.8 m x 1.3 m containing two scintillator panels. Each panel is composed of 24 extruded scintillator bars (1600x50x10

https://doi.org/10.1051/epjconf/202328306001

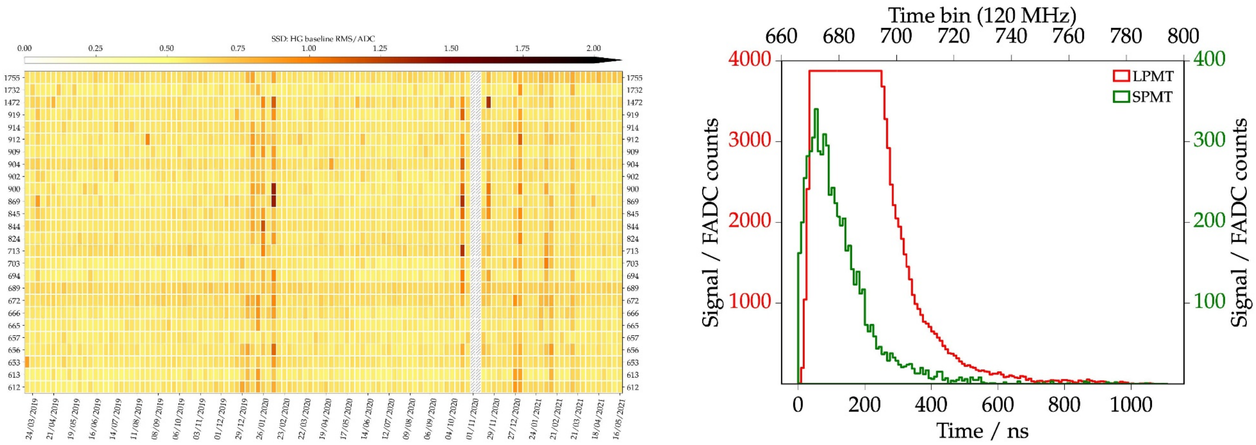

Figure 2. Left: evolution of the baseline of the PMTs high gain trace for a subsample of SSD of the preproduction array. Right: large PMT (LPMT) and small PMT (SPMT) signals in a detection station: the anode channel of the LPMT is clearly saturated (red), while the SPMT is providing an unsaturated signal (green).

mm). The scintillation light produced by particles is collected with wavelength-shifting fibres inserted into 2 straight extruded holes in the bars. The 1 mm diameter fibers (Kuraray Y11(300)M S-type) are positioned following the grooves of the routers at both ends in a U-configuration. The fiber ends are all together bundled in a PMMA cylinder and optically coupled to a single 1.5 inch photomultiplier tube (Hamamatsu R9420), with 18% quantum efficiency at 500 nm. The power supply of the PMT is based on a custom-made design manufactured by the ISEG company. Two PMT channels are available: high gain (amplified anode signal) and low gain (attenuated anode signal) with a factor of 32 between them. With these two channels, the dynamic range of the SSD spans from the signal of a single particle, mandatory for calibration purpose, to large signals, up to more than 10000 Minimum Ionizing Particles (MIP)s. The two scintillator panels are housed in a light and waterproof aluminium casing. In addition, a second roof is installed to provide thermal protection. The SSD module is attached to the top of the WCD tank using a support frame designed to withstand environmental conditions, particularly high winds.

A total of 1518 SSD units have been assembled and tested in seven European research institutes [15], members of the Pierre Auger Collaboration. Using atmospheric muons, the light tightness of each module has been checked, and the charge over peak of the MIP signal has been measured. The MIP is the unit for the SSD signal calibration, as the VEM is used for the WCD signal calibration. The number of photo-electrons per MIP was also measured to check the quality of each assembled module, and the obtained mean value is around (30 ± 2) photo-electrons per MIP. The uniformity in the response of the SSD detectors has been studied on a sample of detectors using external trackers on a muon tower setup. The linearity has been checked to be 5% in one scintillator bar, and 10% between bars. All photomultipliers to be installed in the SSD modules for converting the collected light have been tested in two European research institutes. Their characteristics have been validated, in particular their linear response when operated at low gain.

2.2 Additional small photomultiplier tube

As previously mentioned, for the purpose of extending the dynamic range of the signal acquisition, the WCD is equipped with an additional small photomultiplier tube, installed on an available view port on the tank liner, located close to one of the three large PMTs (LPMT). The photomultiplier tubes are Hamamatsu R8619 1-inch diameter ones, with passive base, and the power supply in a separate box [16]. Linearity and gain curves of each SPMT were carefully measured [17].

2.3 Upgraded Unified Board

The functionalities of the Upgraded Unified Board should at least be the same as the current one, but extended in performances and adapted to new detectors: analog signal processing, GPS time tagging, triggering, calibration, data acquisition, communications via radio transmitter [18]. It has also to provide interfaces with UMD and RD systems. Compared to the Phase I unified board, its capabilities have been improved: FADCs with higher sampling rate (from 40 to 120 MHz), larger dynamic range (from 10 to 12 bits), more accurate time tagging, significantly more powerful FPGA, upgraded CPU (more than 10 times faster). It is designed to ensure mechanical compatibility, by fitting the enclosure of current electronics, and accepting the existing connection cables. Backward compatibility with the current dataset are also maintained; in particular digital filtering and trace down-sampling are provided to emulate current triggers in addition to any new triggers. The design goals also include improved reliability and ease of maintenance.

The boards production started on January 2020, by the A4F (formely SITAEL SpA) company. Boards are tested after production, and environmental stress screening tests

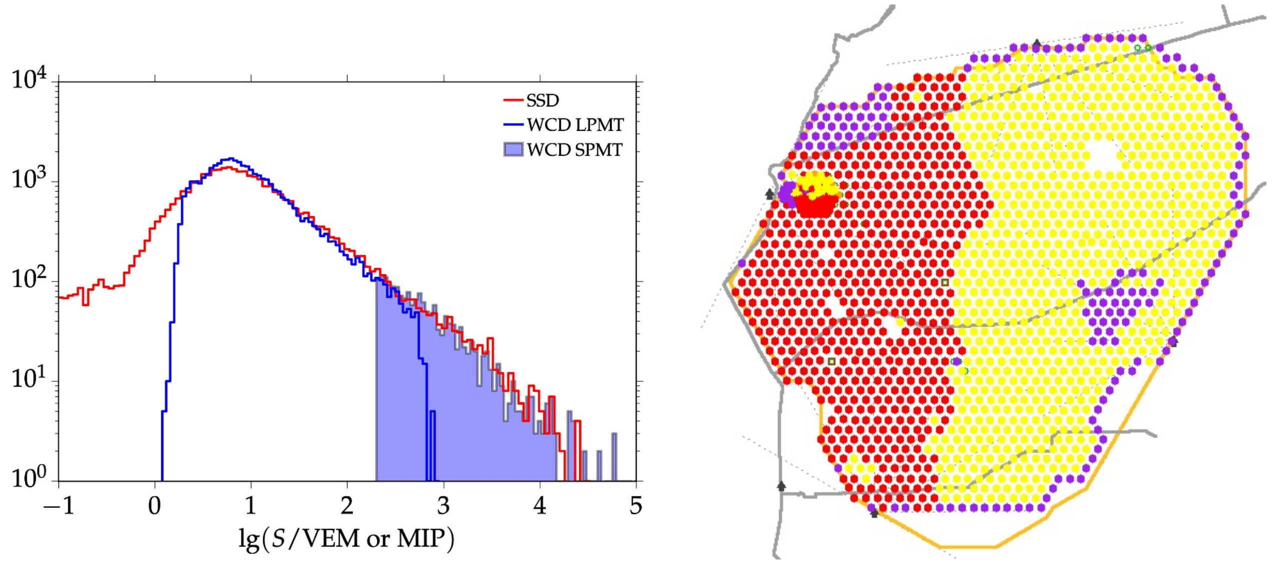

Figure 3. Left: The dynamic range of both WCD (blue) and SSD (red). The extension of the WCD dynamic range is obtained thanks to the SPMT. Right: map showing the status of the AugerPrime deployment on 03/10/2022. Red dots: WCD+SSD+UUB stations (except on the border) ; yellow dots: WCD+SSD; purple dots: WCD only.

are done in one European research institute of the Pierre Auger collaboration, before delivery to Argentina.

3 Pre-production array

SSD modules, SSD-PMTs and SPMT, once ready and tested, have been shipped to the Pierre Auger Observatory. To check the performances in situ, a pre-production array of 77 SSD was deployed in March 2019. The reading of the SSD-PMTs output was performed using a specific electronic module to adapt the PMT signal to the Phase I electronics (1 LPMT of the WCD had to be disconnected to free one channel and connect the SSD PMT).

The pre-production array has been monitored during several months, the behaviour of the SSD modules has been controlled, and the SSD parameter values checked, as well as the SPMT ones [19]. As an example, the evolution of the baseline of the PMTs trace (high gain channel) for a subsample of SSD of the preproduction array is shown in Fig. 2, left. In the vertical axis the identification numbers of the WCD are reported. The color uniformity along horizontal rows clearly shows the stability of the detectors. The vertical patterns signal the occurrence of thunderstorms or temporary communication default in the SD array. When comparing the amplitude of the baseline variations during days and nights, no difference has been found, confirming the light tightness of the SSD modules.

The SPMT have been also evaluated in the AugerPrime Engineering Array[3] (several upgraded detection stations), using UUB modules being tested in the fields. The SPMT active area being almost 100 times smaller than the LPMT one, with the appropriate gain value, the signal produced in a WCD as close as ~250 m from the shower core is unsaturated (Fig. 2, right). The signals in the WCD are measured up to saturation (around 700 VEM) by the LPMTs in the WCD tanks, and above the saturation region, they are derived from the SPMT: the non saturated range of the WCD extends to more than 20000 VEM (Fig. 3, left).

4 AugerPrime commissionning

4.1 Deployment status

The installation of the SSD modules on top of each WCD, over the 3000 km^2 in the pampa, started at the end of 2018. In spite of the COVID-19 pandemic, and the sometimes harsh conditions of access to the WCD, the deployment of the SSD was completed (except on the boarder, as planned, and in two particular areas, as it is impossible to access them) in March 2022. The deployment of the new electronics and the installation of the SPMT started in December 2020. In October 2022, thanks to the strong commitment and effort from the staff in Malargüe, more than 30% of the array has been upgraded (see Fig. 3, right). The production of electronics boards should be completed in January 2023, and the deployment will continue up to mid-2023.

4.2 Measured performances

Since beginning of 2021, the behaviour of the increasing part of the array which is upgraded is studied, and available data are analyzed. The data acquisition system of the Observatory has been running without major interruption. All triggers run at 40 MHz, to ensure backward compatibility, until the full upgrade of the array. Nevertheless, the traces with the binning corresponding to 120 MHz are recorded to benefit of the high sampling provided by the

---

[3] Started in 2016, an Engineering Array of twelve upgraded stations, with detector and electronic board prototypes has been taking data in the SD array.

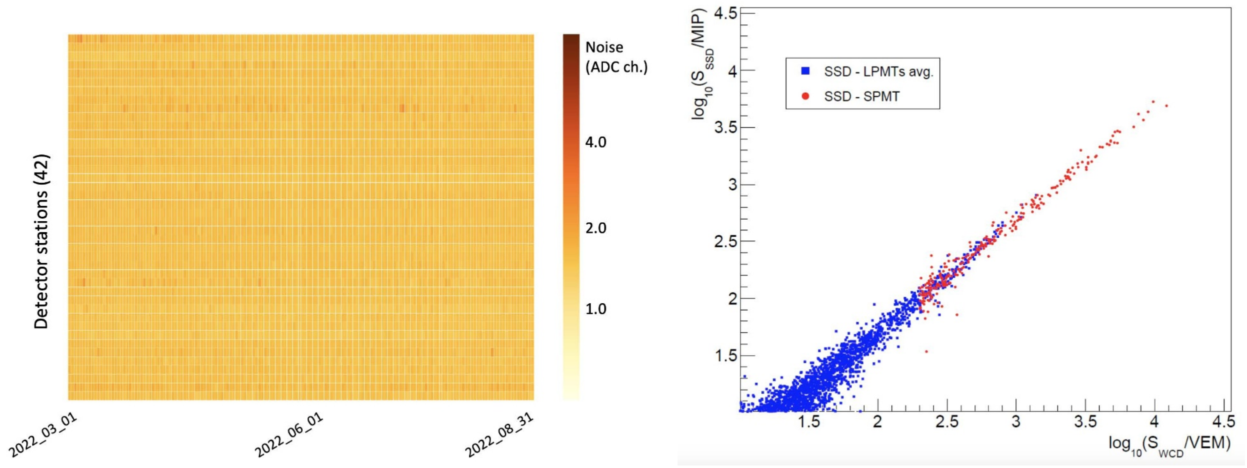

Figure 4. Left: RMS(baseline, high gain channel) of large PMTs as a function of time for a sub-sample of upgraded stations running without interruption. Right: Correlation between SSD and WCD signals. For the WCD, the large PMTs are used up to the saturation (blue dots); the measurements are extended further by the small PMT (red dots).

new electronics. Each SSD unit is triggered by the associated WCD, in a slave-mode.

For each upgraded detection station, composed by one WCD plus one SSD unit, the baselines of the 5 PMTs (3 LPMTs, 1 SPMT, 1 SSD-PMT) are constantly monitored. The fluctuations show that the level of noise is in the expected range, being below 2 FADC channels for the high-gain channel of the LPMTs (Fig. 4, left). The time resolution, measured using a set of showers triggering two nearby stations, is found to be in the order of 5 ns. Some issues concerning the GPS time tagging and the trigger rates were observed and are being resolved.

4.3 AugerPrime calibration

As explained in 1 and 2.2, the WCD signals are expressed in terms of VEM units, and the SSD signals in MIP. Signal calibration, which converts electronic units in VEM or MIP units, is performed using atmospheric muon signals acquired by dedicated triggers. About 40% of WCD calibration triggers produce a MIP in the SSD.

Due to the small sensitive area of the SPMT, it is not possible to calibrate their signals with the atmospheric muons. Instead, small local showers are selected to cross-calibrate SPMT using the VEM signals of the LPMTs. A very good correlation between the calibrated signals of the WCD (large and small PMTs) and the SSD is obtained (Fig. 4, right), on the full dynamic range, up to 20000 VEM. The calibration parameters (VEM, MIP) are constantly monitored, and a good stability of the corresponding values is observed. The possibility to improve WCD calibration taking advantage of the SSD is currently under study.

4.4 Reconstruction of events

The reconstruction of events with the SD data applied during Phase I is described in detail in [20]. Algorithms in the reconstruction process need to be revised to incorporate the information provided by the new detectors, in order to benefit from their valuable inputs.

Once the signals, measured by the individual detectors, including the SSDs, have been properly calibrated, they can be used in the reconstruction of the showers. After correctly defining the time integration range of the SSD signal corresponding to the passage of the shower particles, the uncertainties in the measured signals were quantified and shown to be proportional to the square root of the signal, with a proportionality coefficient depending on the zenith angle [21].

Algorithms have been developed for reconstructing shower-size estimator for SSD as complement to WCD estimator. These two shower size estimates are expected to allow the deconvolution of the relative intensity of the muonic and electromagnetic components of air showers. The signal as a function of the distance to the shower axis is expressed as $S(r) = S(r_{\mathrm{opt}})f_{NKG}(r)$, using a modified NKG-like function, expressed by

$$f_{NKG}(r) = \left(\frac{r}{r_{\mathrm{opt}}}\right)^{\beta}\left(\frac{r+r_s}{r_{\mathrm{opt}}}\right)^{\beta+\gamma}$$

The optimal distance r_{opt}, largely driven by detector spacing and array geometry, has been set to 1000 m for the SD in the event reconstruction [20]. Considering that SSDs and WCDs are co-located, the same value is adopted for the reconstruction of the LDF using the SSD signals. An example of the lateral distributions measured by both SSD and WCD are displayed in Fig. 5, showing different slopes. Nevertheless there is room for improvements, searching for more appropriate LDFs. Up to now, only the shower size at 1000 m is fitted, but for events with high SSD multiplicity, it will be possible to fit the LDF slope. More sophisticated algorithms using also the time structure of traces, and not only the signal magnitudes are in development.

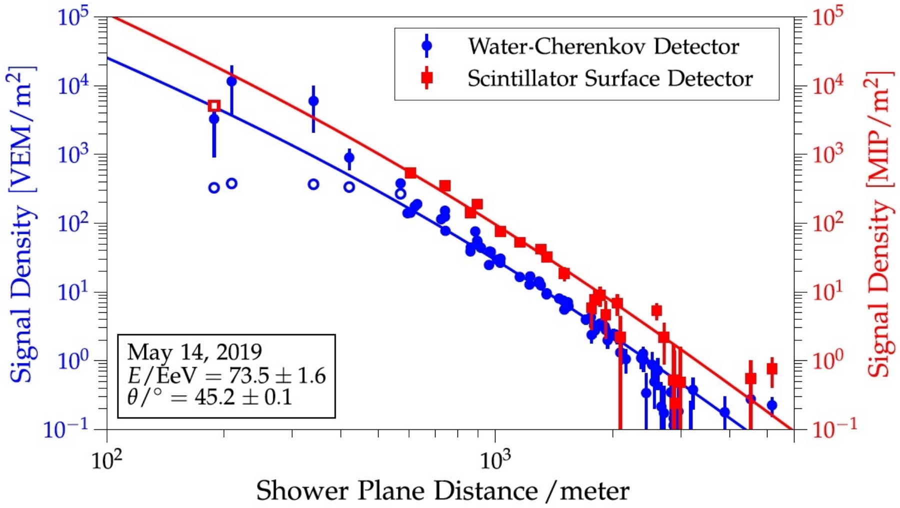

Figure 5. Exemple of a high-energy event measured in the pre-production array. The WCD (blue) and SSD (red) signal density are plotted as a function of the shower plane distance. Both corresponding fitted LDFs are shown.

5 Outlook

The objective of AugerPrime is to obtain enhanced composition information on the UHECR detected by the Pierre Auger Observatory, to answer still open questions on the origin of these astroparticles. It will provide a multi-hybrid cosmic ray detector, that will allow simultaneous measurement of a shower with water-Cherenkov detectors, surface scintillator detectors, radio detectors, muon counters and fluorescence detectors. Operation of the full upgraded Observatory is expected from 2023 to 2030, the goal being to reach an exposure of ~ 40000km^2 sr yr for vertical events, i.e. those with a zenith angle below 60°.

More than 30% of the detection stations of the SD have been equipped with scintillator detectors, one additional small PMT in the water-Cherenkov detector and new electronics, allowing data taking and commissionning procedures. A stable behaviour of the different detectors is observed. Event reconstruction using information from the scintillation is underway, results are promising, and several studies are going on to improve it, based on principles of air shower universality or using machine learning techniques. Development of methods to deconvolve the contributions of the electromagnetic and muonic shower components are on-going, moving towards primary mass identification.

References

[1] The Pierre Auger Collaboration, Nucl. Instrum. Meth. **A 798** 172-213 (2015)

[2] X. Bertou, et al., Pierre Auger Collaboration, Nucl. Instr. and Meth. **A 568** 839 (2006)

[3] The Pierre Auger Collaboration, Phys. Rev. **D 93** 122005 (2016)

[4] The Pierre Auger Collaboration, Eur. Phys. J. **C 80** 751 (2020)

[5] The Pierre Auger Collaboration, Eur. Phys. J. **C 81** 966 (2021)

[6] A. Yushkov for the Pierre Auger Collaboration, Proceeding of Science, 37th International Cosmic Ray Conference, 358 (2021).

[7] The Pierre Auger Collaboration, Universe **8** 579, (2022)

[8] Karl-Heinz Kampert, Miguel Alejandro Mostafa, Enrique Zas and The Pierre Auger Collaboration, Front. Astron. Space Sci. **6** 24 (2019)

[9] The Pierre Auger Collaboration, ApJ **868** 4 (2018)

[10] The Pierre Auger Collaboration, ApJ **935** 170 (2022).

[11] E. Guido, for the Pierre Auger Collaboration, PoS(ICRC2021)311

[12] D. Soldin, PoS(ICRC2021)349

[13] T. Huege, for the Pierre Auger Collaboration, in these proceedings.

[14] M. Scornavacche , for the Pierre Auger Collaboration, in these proceedings.

[15] J. Pekala, for the Pierre Auger Collaboration, PoS(ICRC2019)380

[16] G.A. Anastasi et al., JINST **17** T04003 (2022)

[17] M. Buscemi et al., JINST **15** P07011) (2020).

[18] G. Marsella for the Pierre Auger Collaboration, PoS(ICRC2021)230.

[19] G. Cataldi for the Pierre Auger Collaboration, PoS(ICRC2021)251.

[20] The Pierre Auger Collaboration, JINST 15 P10021 (2020)

[21] D. Schmidt, for the Pierre Auger Collaboration, PoS(ICRC2021)218