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# Auger@TA: An Auger-like surface detector micro-array embedded within the Telescope Array Project

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The Pierre Auger Observatory (Auger) and the Telescope Array Project (TA) are the two largest ultra-high-energy cosmic ray (UHECR) observatories in the world. One obstacle in pursuing full-sky UHECR physics is the apparent discrepancy in flux measured by the two experiments. This could be due to astrophysical differences as Auger and TA observe the Southern and Northern skies, respectively. However, the scintillation detectors used by TA have very different sensitivity to the various components of extensive air showers than the water-Cherenkov detectors (WCD) used by Auger. The discrepancy could also be due to systematic effects arising from the differing detector designs and reconstruction methods. The primary goal of the Auger@TA working group is to cross-calibrate the approaches of the two observatories using in-situ methods. This is achieved by placing a self-triggering micro-array, which consists of eight Auger surface detector stations, with both WCDs and AugerPrime scintillators, within the TA array. Seven of the WCDs use a 1-PMT prototype configuration and form a hexagon with the Auger spacing of 1.5 km. The eighth station uses a standard 3-PMT Auger WCD, placed with a TA station at the center of the hexagon to form a triplet for high-statistics, low-uncertainty, cross-calibration of instrumentation. Deployment of the micro-array took place between September 2022 and August 2023, with data-taking foreseen by the Fall of 2023. Details on the instrumentation and deployment of the micro-array, as well as its expected performance, trigger efficiencies, and event rate will be presented. First data from individual stations will also be shown.

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## 1. Introduction

The Pierre Auger Observatory (Auger) [1] and the Telescope Array Project (TA) [2] are the two largest experiments in the world that study ultra-high-energy cosmic rays (UHECR). They are located in opposite hemispheres - the Pierre Auger Observatory in the Southern hemisphere and the Telescope Array Project in the Northern hemisphere - and have collected data over the past 15 years, finding that their results are not entirely consistent. A notable discrepancy between the two observatories is a difference in the measured energy scale of UHECR between the two experiments shown in Figure 1. One aspect of this is a difference of approximately 9 %, falling within the range of systematic uncertainties for both experiments, which until now has been resolved through re-scaling. Even after re-scaling, a residual energy scale difference increasing with energy from the the start of the suppression region and beyond remains and cannot be resolved easily [3].

There are two possible reasons for these discrepancies. They could be caused by fundamental differences between the northern and southern UHECR skies, they could originate from undetermined discrepancies in the way data is processed by the two experiments, or both. With an on-going and increasing collaboration between Auger and TA, it is now crucial to ascertain the cause of the observed differences, to allow for further joint high-level, full-sky analyses [4–6].

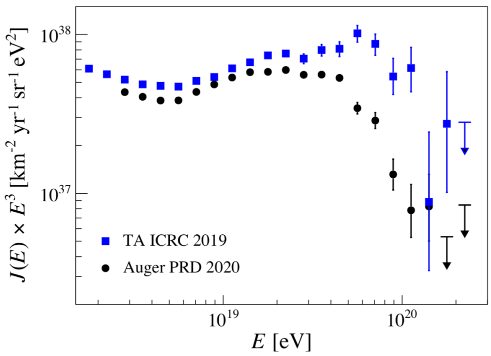



**Figure 1:** Measured UHECR flux: Auger (black circles) and TA (blue squares) (adapted from [3]).

## 2. The Auger@TA Project

Both experiments use surface detectors (SDs) as their main statistics driver, but they employ different designs. The Auger SD uses a Water Cherenkov detection (WCD) system to collect light produced by charged particles above a certain energy threshold and is sensitive to both the electromagnetic and muonic component of an air shower. The TA SD uses plastic scintillators as particle counters which have an equal per-particle response to the electromagnetic and muonic part of the shower. However, since the electromagnetic component of the shower often has a higher particle count, the signal in scintillator detectors is often dominated by the electromagnetic component. The Auger SD is calibrated to the signal of a muon passing vertically through the tank (VEM), while the baseline calibration unit for the TA SD is the Minimum Ionizing Particle (MIP) energy loss. To compare the two detectors, the Auger@TA project was formed, consisting of around two dozen members from both experiments. The project aims to cross-calibrate the SDs of both experiments using Auger detectors at the Telescope Array site and measuring the same showers. The Auger@TA initiative has outlined goals in ascending order of required statistics which are listed below and described in more detail in [7].

- Cross-calibration of Auger and TA SDs (station-by-station level)
- Event reconstruction comparison (event-by-event level)
- Test nature of 9 % energy scale difference by making a fully independent flux measurement

- Investigate discrepancy in flux suppression region with single event comparisons

The Auger@TA project is conducted in two stages, with Stage I spanning from 2018 to 2020 and Stage II currently ongoing. Both stages will be reported on in this document, with a full publication on Stage I following later this year.

## 3. Auger@TA Stage I: Station-level Comparisons

The initial stage of the Auger@TA project had the goal of cross-calibrating and comparing the data from two co-located stations, one regular 3-PMT Auger (here Auger@TA) and one TA station, positioned at the TA Central Laser Facility (CLF) [8, 9]. The TA station received a trigger signal from the TA array and data from both stations were recorded. Over the course of the run-time of Stage I, a total of 12 events, that were reconstructed by TA and passed their quality cuts, were observed by the co-located Auger@TA and TA stations. For each of the 12 shared events, similar events were selected from nearly 20 years of available Auger SD data, in order to analyze the Auger@TA signal and compare it to both the Auger and TA array.

The TA reconstruction values for energy and zenith, $E_{\text{rec}}^{\text{TA}}$ and $\theta_{\text{rec}}^{\text{TA}}$, were used to select all Auger events that are within a $1\sigma\,(E_{\text{rec}})$ window of the TA reconstruction values. In order to calculate this $1\sigma\,(E_{\text{rec}})$ window the TA reconstruction uncertainties as reported by TA in [2] as well as the energy and zenith uncertainties from Auger as reported in [10] and [1] are taken into account and added in quadrature as

| Event ID | $E_{\text{rec}}^{\text{TA}}$ (EeV) | $\theta_{\text{rec}}^{\text{TA}}$ (°) | $S_{\text{TA}}$ (MIP) | $S_{\text{Auger@TA}}$ (VEM) | $R_{\text{Auger@TA}}$ (m) | $\#Events_{\text{Auger}}$ | Quantile (%) |
|---|---|---|---|---|---|---|---|
| 12 | 4.25 | 43.52 | 8.39 | 18.97 | 1078 | 9496 | 75.3 |
| 13 | 3.61 | 40.74 | 27.42 | 40.33 | 703 | 13807 | 26.7 |
| 34 | 4.57 | 38.44 | 18.51 | 25.12 | 1105 | 7505 | 89.5 |
| 49 | 4.58 | 38.28 | 38.83 | 56.49 | 811 | 7402 | 68.2 |
| 80 | 7.57 | 22.23 | 6.43 | 6.85 | 1580 | 1769 | 49.9 |
| 90 | 3.30 | 5.41 | 16.55 | 31.99 | 1016 | 2623 | 93.7 |
| 105 | 4.84 | 31.94 | 523.74 | 505.66 | 382 | 6073 | 40.5 |
| 111 | 4.96 | 39.92 | 8.33 | 6.71 | 1318 | 6317 | 17.8 |
| 119 | 4.93 | 32.64 | 51.48 | 104.31 | 775 | 5809 | 84.6 |
| 165 | 4.24 | 22.79 | 8.66 | 11.74 | 967 | 6334 | 2.3 |
| 181 | 3.24 | 16.29 | 68.70 | 86.16 | 355 | 9114 | 0.4 |
| 188 | 3.11 | 41.15 | 12.54 | 50.61 | 857 | 29429 | 94.3 |

**Table 1:** Overview of the 12 shared events observed in Stage I (see text for details).

$$\sigma\,(E_{\text{rec}}) = \sqrt{\sigma\left(E_{\text{rec}}^{\text{TA}}\right)^2 + \sigma\left(E_{\text{rec}}^{\text{Auger}}\right)^2} \quad \text{and} \quad \sigma\,(\theta_{\text{rec}}) = \sqrt{\sigma\left(\theta_{\text{rec}}^{\text{TA}}\right)^2 + \sigma\left(\theta_{\text{rec}}^{\text{Auger}}\right)^2} \tag{1}$$

The number of selected Auger events is listed for each of the 12 Stage I events in Table 1. An average lateral distribution function (LDF) [11] is calculated from the Auger events in order to compare it to the Auger@TA signal for each of the 12 Stage I events. If the Auger@TA signal is above the average LDF this means that the $E_{\text{rec}}^{\text{TA}}$ used to select the Auger events was lower than what would be needed to achieve a signal of that size in Auger. The opposite is true when the Auger@TA signal is below the average LDF. An example can be seen in Figure 2.

To eliminate selection effects influencing further analysis the Auger events are weighted. Selection effects originating from the UHECR spectrum are reduced by applying a spectrum weight $w_{E,\text{spec}} = \left(E_{\text{rec}}^{\text{TA}}/E_{\text{rec}}^{\text{Auger}}\right)^{-\gamma}$, where $\gamma$ is the spectral index using the values as reported in [10] for the respective $E_{\text{rec}}^{\text{TA}}$. Additionally for both $E_{\text{rec}}^{\text{TA}}$ and $\theta_{\text{rec}}^{\text{TA}}$, weights ($w_{E,\text{gauss}}$ and $w_{\theta,\text{gauss}}$)

are sampled from Gaussians with $\mu$ as the respective reconstruction value and $\sigma$ is the respective TA+Auger resolution on that value (as mentioned in Equation 1), in order to de-weight events the further they are from the TA reconstruction values. Doing so leads to a combined weight of $w_{\text{Event}} = w_{E,\text{spec}} \cdot w_{E,\text{gauss}} \cdot w_{\theta,\text{gauss}}$. Residual signals are calculated for each Auger event with respect to the associated Auger@TA event as $S_{\text{res}} = \frac{S_{\text{Auger}} - S_{\text{Auger@TA}}}{S_{\text{Auger@TA}}}$ and their weighted distribution is shown in Figure 2.

The quantiles, shown in Table 1, are calculated as $q = (A_{\text{under}}/A_{\text{total}}) \cdot 100$ (with $A_{\text{under}} = \sum w_{\text{Event}}(S_{\text{res}} \leq 0)$ and $A_{\text{total}} = \sum w_{\text{Event}}$). They describe the percentage of $S_{\text{Auger}}$ that were lower than $S_{\text{Auger@TA}}$. Due to the very low statistics of 12 events, there is no clear trend visible that would indicate Auger@TA yielding different results than Auger. This is also reflected in the fact that about half of the events are in the quantile above 50 % and the other half is in the quantile below 50 %. There are only two events that are significant with more than 90 % of the selected Auger events having a lower signal than the one measured with Auger@TA. The analysis of Stage I data and its interpretation is currently being finalized and will be reviewed by both collaborations prior to publication later this year.

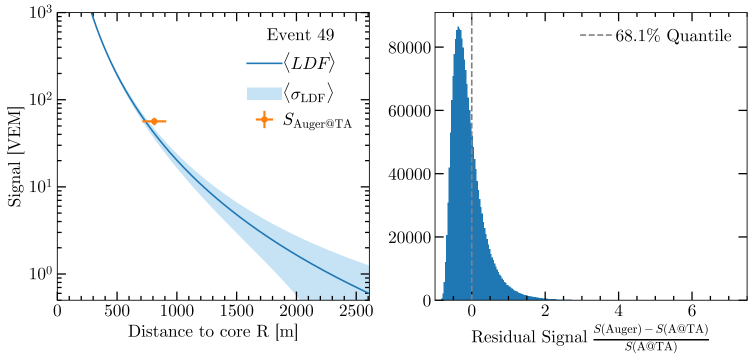



**Figure 2:** Auger@TA Stage I event 49: Left: Signal from Auger@TA station (orange data point) in relation to average Auger LDF (blue line and error band). Right: Weighted distribution of $S_{\text{res}}$.

## 4. Auger@TA Stage II: Extension to Event-level Comparisons

Auger@TA Stage II is an extension of Stage I, involving station-level comparisons as well as direct comparisons of Auger and TA shower reconstructions. This study is necessary due to significant differences in the two SD reconstruction methods. Auger and TA both use a shower size estimator obtained from their respective LDFs. However, they differ in how they convert this estimator into a normalized quantity. Auger uses a Constant Intensity Cut method [12, 13] while TA relies on large shower simulation libraries [14]. For a comparison of reconstruction parameters, more than two stations are needed.

Stage II will use seven 1-PMT prototype stations, previously used for R&D of a Northern hemisphere Auger [15], arranged in a hexagon pattern, spaced 1.5 km apart, to enhance statistical accuracy. The regular 3-PMT Auger station and the TA station from Stage I are placed at the center of the hexagon as well, forming a triplet. The spacing in the triplet is approximately 11 meters, which is the same distance used for doublet and triplet setups by Auger [16] and was chosen to minimize reconstruction biases when using the fine-tuned reconstruction procedure developed for the Auger Observatory. The central triplet will provide high statistics for studying signal correlations between the 1- and 3-PMT Auger stations (in VEM) and the TA station (in MIP). This will allow for cross-calibration and the extension of the Stage I study.

### 4.1 The Auger@TA station & Communications System

The stations in the hexagon that were sourced from the 1-PMT prototype stations were retrofitted to match regular Auger stations as closely as possible. The retro-fitting process and an overview of the new components are described in detail in [7] and a schematic of one such Auger@TA station can be seen in Figure 3. The only differences now remaining between a standard Auger and an Auger@TA station are the number of PMTs (one central PMT), the form factor of the shell (minor), and the custom-designed communications system using off-the-shelf components.

All eight Auger-type stations are also outfitted with an AugerPrime Surface Scintillator Detector (SSD) [17]. These SSDs expand on the original scope of placing a micro-array in TA and allow for further cross-calibration options.

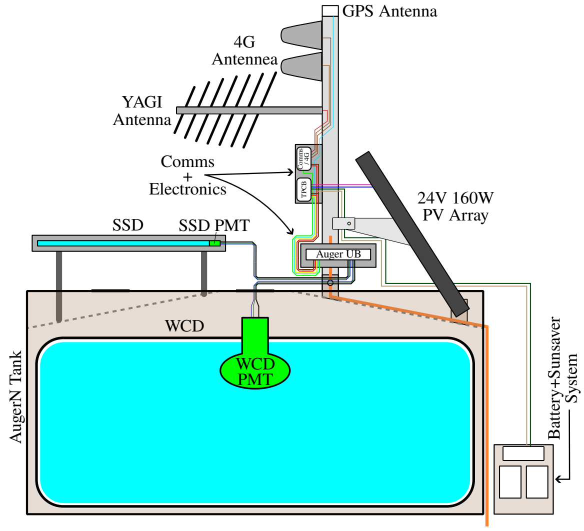


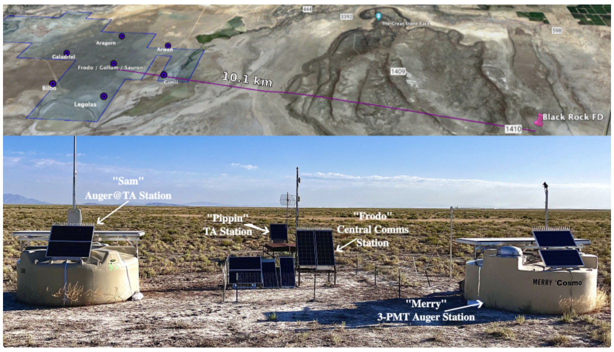

**Figure 3:** Auger@TA station schematic.

The micro-array has a custom communications system that utilizes easily available components, allowing for direct internet access to the stations. YAGI antennas with Digi Xbee Pro transceivers are used to ensure communication between the central triplet and the stations located on the outside of the hexagon. An abstraction layer is implemented over the Xbee line for internet access. Science data and commands are still relayed via regular Auger protocols for debugging. A mobile 4G LTE wireless modem is used for communication from the central node to the data server located at Case Western Reserve University.

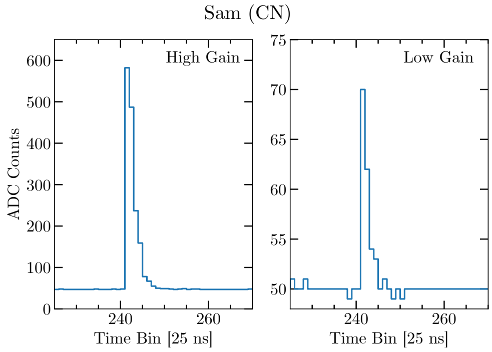
### 4.2 Status of the Micro-array & First Data

The Auger@TA micro-array has been deployed in the southwest corner of the TA array overlooked by the Black Rock fluorescence detector (FD) (see Figure 4a). In September 2022, the main stage of deployment was completed.

The initial deployment involved decommissioning the Stage I setup and inspecting all 8 stations before placing the detector stations and supporting equipment in the selected area. The deployment site is shown in Figure 4a in relation to Black Rock FD. Water delivery occurred in the weeks following deployment and station commissioning took place over subsequent trips this year. Commissioning of the micro-array is nearing completion with most stations only missing PMT bases (supply chain issues) and the SSDs, which need to be deployed after placing the bases due to accessibility. However, the two Auger-type stations in the central triplet have been fully commissioned and can be seen in Figure 4a. A first set of raw signal traces that has been obtained from the Auger@TA station in the central triplet can be seen in Figure 4b. The remaining SSDs and PMT bases will be placed at the beginning of August. A fully instrumented micro-array is expected by the end of August 2023.




**(a)** Top: Location of the 9 station micro-array within TA, also showing the distance to the Black Rock FD. Bottom: Center triplet and data acquisition comms station. Station names inspired by [18].




**(b)** High gain (left) and low gain (right) channel signal traces obtained from the WCD PMT of the Auger@TA central triplet station.

**Figure 4:** Deployment site and first station data.

### 4.3 Expected Performance: Energy Resolution

To ensure the success of Auger@TA, a high-quality energy reconstruction is critical. However, achieving this with only one hexagon is challenging.

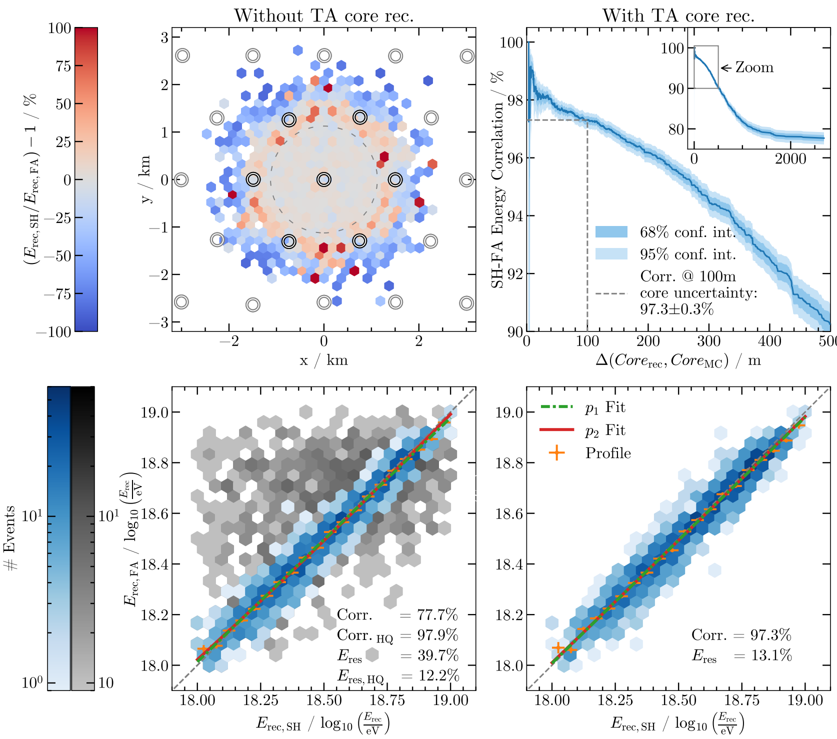



**Figure 5:** Expected energy resolution: Left panels: All reconstructed events (grey in bottom) compared to HQ selection (blue in bottom). Right panels: Extrapolated SH energy resolution assuming TA core uncertainty of ≈ 100 m can be used (detail in text).

Using the regular full Auger array (FA) to benchmark the single hexagon (SH) performance by running a simulation study and comparing all successfully reconstructed events from both simulation sets, the energy resolution of the single hexagon, calculated over the full simulated energy range, is only 39.7 % (see Figure 5 bottom left) without any quality cuts. It is expected that events with a shower footprint, or shower core falling within a single hexagon will have better reconstruction on average, as can be verified in the top left plot in Figure 5. To select high-quality events, a cut is made on the distance of the reconstructed shower core to the central station ($R_{\text{center}} \leq 1125\,\text{m}$). This high-quality selection cut greatly improves the energy resolution of the single hexagon to 12.2 % (see also Figure 5 bottom left).

Reducing the number of usable events in the data set is, of course, not ideal, and such a selection will only be applied for completely independent Auger@TA studies. Nonetheless, usually events seen by the micro-array will also likely be observed by TA. Thus, using the TA shower core reconstruction in the Auger@TA reconstruction can be done with minimal bias. A study of the possible effect of this on the energy resolution can be seen in Figure 5 in the panels on the right. Here the correlation between SH and FA simulation as a function of the the SH core reconstruction uncertainty is investigated. To emulate what the result of using the TA core reconstruction to inform the SH reconstruction could be, the SH-FA correlation is evaluated by looking only at events which have a core reconstruction uncertainty of $\approx 100\,\text{m}$ or better. This value was chosen as it is equivalent to the TA shower core uncertainty at low energies [14]. Doing so achieves an energy resolution of 13.1 %, which is comparable to the high-quality cut of 12.2 %.

### 4.4 Expected Performance: Event Rate

The single hexagon simulation set can be used to predict the yearly event rate when folding in the UHECR spectrum for the micro-array (see Figure 6). To select a suitable region for measuring the cosmic ray flux the reconstructed energy distribution was compared to the thrown Monte Carlo and a flat region from 18.3 – 18.8 $\log_{10}(E/\text{eV})$ was selected. The expected statistics in this region are up to 65 events/yr when assuming that the TA core reconstruction can be used as explained above. Assuming this event rate, a flux measurement could be made after two years with 8.7 % statistical uncertainty, leading to a $1\sigma$ level comparison between Auger and TA. Seven years would be needed for a $2\sigma$ level comparison unless lower energy events can be included. Systematic uncertainties are still being quantified, and the simulations will be refined to optimize the study.

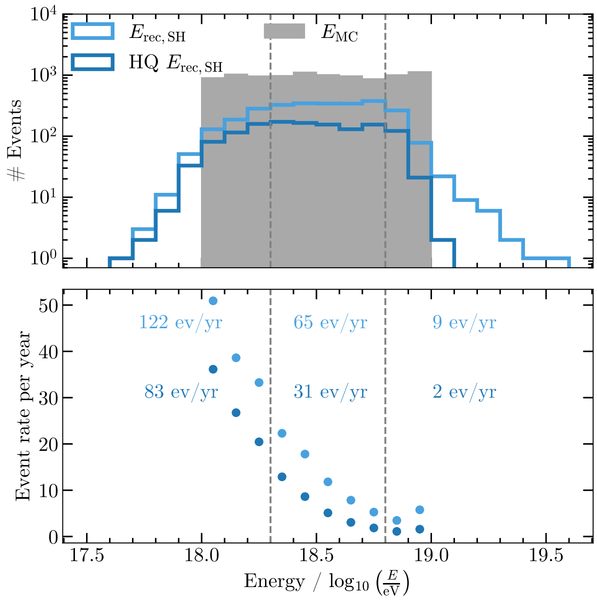



**Figure 6:** Expected event rates: Both plots: light blue: all $E_{\text{rec}}$ data, dark blue: high-quality selection (see Figure 5), x-axis energy refers to $E_{\text{rec}}$ for blue histograms and $E_{\text{MC}}$ values for grey histogram. Top: $E_{\text{MC}}$ distribution (filled grey histogram) and $E_{\text{rec}}$ distributions (blue histograms) shown together with selected flux measurement region (dashed lines). Bottom: Predicted event rate with numbers for each region.

## 5. Summary and Outlook

The Auger@TA project is currently the only effort that can identify differences in the Auger and TA SD data by measuring the same showers with the two different detector types. This is needed to determine if the energy scale discrepancies between the experiments are due to astrophysical differences or unresolved data analysis discrepancies.

During Stage I of the project, 12 events were collected that were observed both with co-located Auger and a TA stations as well as with the TA array itself. The analysis of these events, although statistically limited, has already yielded positive results. There is currently no clear indication of the Auger@TA station of Stage I giving different results as compared to the Auger SD array. A full analysis of the Stage I data will be released later this year.

Stage II is currently in progress, with the micro-array almost fully instrumented and the first data expected by the second half of 2023. The remaining parts of commissioning are the deployment of bases and SSDs in the outer-hexagon stations. The first traces from one of the stations in the central triplet are shown in this document. Simulation studies have been carried out to gauge the expected performance of a single hexagon array and the results look promising, with a $1\sigma$ level comparison between Auger and TA potentially being possible after two years of data taking.

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## The Telescope Array Project

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