Auger@TA: Deploying an independent Pierre Auger Observatory SD micro-array at the Telescope Array Project

Auger@TA Working Group Report

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Abstract. The Pierre Auger Observatory (Auger) and the Telescope Array Project (TA) are the two largest ultra-high-energy cosmic ray observatories in the world. They operate in the Southern and Northern hemispheres, respectively, at similar latitudes but with different surface detector (SD) designs. This difference in detector design changes their sensitivity to the various components of extensive air showers. The over-arching goal of the Auger@TA working group is to cross-calibrate the SD arrays of the two observatories in order to identify or rule out systematic causes for the apparent differences in the flux measured at Auger and TA. The project itself is divided into two phases. Phase-I finished in 2020 and consisted of a station-level comparison facilitated by the deployment of two Auger stations, one prototype station with a single central PMT and a standard Auger station, in the middle of the TA SD near the Central Laser Facility, along with a modified TA station to provide external triggers from the TA SD. This provided the opportunity to observe the same extensive air showers with both Auger and TA detectors to directly compare their measurements. Phase-II of Auger@TA is currently underway and aims at building a self-triggering micro-Auger-array inside the TA array. This micro-array consists of eight Auger stations, seven of which use a 1-PMT prototype configuration and form a single hexagon with a traditional 1.5 km Auger spacing. The 8th station is of the standard Auger 3-PMT configuration and is placed at the center of the hexagon, along with a TA station to form a triplet. Each Auger station will also be outfitted with an AugerPrime Surface Scintillator Detector. A custom communication system using readily available components will be used to provide communication between the stations and remote access to each station via a central communications station. The deployment of the micro-array took place at the end of September 2022. A simulation study was carried out to gauge the expected performance of the Auger@TA micro-array and to derive trigger efficiencies and event rates.

1 Introduction

Currently, the two largest ultra-high-energy cosmic ray (UHECR) experiments in the world are the Pierre Auger Observatory (Auger) [1] and the Telescope Array Project (TA) [2]. They operate in different hemispheres at similar latitudes, with the Pierre Auger Observatory in the Southern hemisphere and the Telescope Array Project in the Northern hemisphere. In the last 15 years, both experiments have gathered large amounts of data, but have found their results differ. One such difference is apparent in the measured flux of both experiments and is illustrated in Figure 1. There appears to be a discrepancy of about 9 % between the energy scales of the two experiments [3]. This is within the range of the systematic uncertainties for both experiments and could possibly be addressed via

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re-scaling. However, a large difference in measured flux would remain at the start of the flux suppression region and beyond.

These discrepancies could be due to fundamental differences between the northern and southern UHECR skies or could be due to unresolved discrepancies in the way the two experiments process extensive air shower (EAS) data. As the collaboration between the two experiments grows, it is becoming more and more important to figure out the reason(s) for the differences between the results of both experiments in order to rule out or correct for instrumental/reconstruction biases. This would then allow for high-level joint analyses to be performed using the combined data from both experiments [4–6].

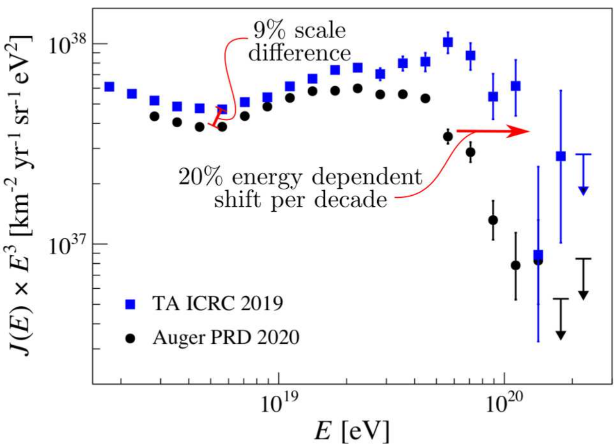

Figure 1: Comparison between the UHECR spectra measured by Auger (black circles) and TA (blue squares). A 9% energy scale difference at the ankle and a growing discrepancy beyond 10^{19}eV is indicated (modified from [3]).

2 The Auger@TA Project

One of the primary similarities between the two experiments is that both use surface detectors (SDs), albeit of very different design, as their main statistics driver. The Auger SD is based on a Water Cherenkov detection (WCD) system, which collects the light produced by charged particles above a certain energy threshold slowing down in the water volume. The baseline unit that all Auger SDs are calibrated to is the energy loss in water of a muon passing vertically through the tank, a Vertical Equivalent Muon (VEM). The WCD is roughly equally sensitive to the electromagnetic and muonic components of a shower. The TA SD instead is based on plastic scintillators that act as particle counters and are predominantly sensitive to the electromagnetic part of the shower, due to electrons being in general more numerous than muons. For scintillators, the baseline calibration unit is the Minimum Ionizing Particle (MIP) energy loss. To directly investigate the impact of these differences, the Auger@TA project was conceived and became an official Auger-TA working group, comprising around a dozen members from both experiments. The central idea behind this project is to perform an in-situ cross-calibration of the SDs of the two experiments by placing Auger detectors at the Telescope Array site and using showers that are measured by both experiments. The central goals of the Auger@TA effort are as follows in order of increasing statistics required.

Cross-calibration of SDs

The most integral aspect for the Auger@TA effort is the cross-calibration of the different SD detector types placed in the field in Utah. The primary difference between them is the detection media used, as they are not equally sensitive to the various components of EASs. The cross-calibration will be achieved by making comparisons on a station-by-station level and studying the different responses seen by the different detector types for each shared event.

Event-by-event reconstruction comparison

By placing a micro-array of seven Auger-like stations in a hexagon configuration within TA, the Auger reconstruction software can be used to reconstruct measured events in order to compare the different detectors and reconstruction techniques on an event-by-event level as well. This can be used to analyze differences in trigger efficiency and zenith dependence, as well as to study shower component dependent systematic differences.

Making a fully independent flux measurement

With the possibility of fully reconstructing events recorded with self-triggering Auger-like detectors in TA, comes the opportunity to potentially make a fully independent flux measurement. This would allow for a direct comparison of the fluxes measured with Auger-like and TA detectors both located in the Northern hemisphere in order to test the nature of the 9 % spectral scale difference.

Test nature of flux suppression discrepancy

If high enough statistics are obtained during the lifetime of the Auger@TA project, it would also be possible to extend the studies mentioned above to higher energies in order to possibly shed light on the nature of the differences as flux suppression kicks in.

The Auger@TA project is divided into two phases. Phase I took place between 2018 and 2020 and aimed at performing a station-to-station *in-situ* cross-calibration using three co-located stations (two Auger, one TA) at the site of the TA Central Laser Facility (CLF) [7, 8]. The two Auger stations used consisted of one regular Auger station from Argentina and one station formerly used in an R&D effort for a Northern hemisphere Auger [9]. These *1-PMT prototype stations*, differ in their number of PMTs (one instead of three) as well as their electronics system, the details of which are not relevant here but are described in [10]. The analysis of Phase I data and its interpretation is currently being finalized and will be reviewed by both collaborations prior to publication later this year.

3 Auger@TA Phase II: Station-by-station and Event-level Comparisons

Auger@TA Phase II is both a continuation and extension of the efforts of Phase I. There will be an expansion of station-level comparisons in order to perform the cross-calibration of detectors, but now it will be possible to also study how the shower reconstructions of Auger and TA perform on the same set of showers and directly compare the results. This study is very much needed as there are significant differences between the way Auger and TA perform their SD reconstructions.

While both Auger and TA rely on a shower size estimator (S(1000) and S(800) respectively) extracted from the lateral distribution function (LDF), there are differences in how the two experiments handle the conversion of this estimator to a quantity normalized against geometric effects, which is eventually calibrated using their respective Fluorescence Detector (FD) energy scale (also known to differ as seen in Figure 1). While Auger uses a Constant Intensity Cut (CIC) method [11, 12] to account for the shower geometry, TA relies on large shower simulation libraries (and a scaling factor) to account for geometric effects [13]. Ideally, such a study should be performed with a large number of stations to push the comparison to the highest energies where the spectrum discrepancy between Auger and TA is the largest. This is unfortunately not realistic at the moment, and comparisons can only be performed using a limited number of stations.

Auger@TA Phase II will do this by making use of all seven remaining 1-PMT prototype stations to build a micro-array. As described below, to lower uncertainties, these stations have been modified to more closely match the regular Auger stations. These stations have been deployed to form a full Auger-like hexagon, with one station in the center, using the same 1.5 km spacing as the southern Auger array. With a full hexagon of stations, the micro-array will provide much higher statistics than were possible in Phase I.

In addition, one regular 3-PMT Auger station and a TA station are also placed at the center of this micro-array to form the triplet illustrated in Figure 2. The operation of the central triplet will provide the high statistics needed to directly study the signal correlations between the Auger 1-PMT and 3-PMT (in VEM), and the TA (in MIP) SD stations, and thus will be used for cross-calibration purposes (thereby allowing for an extension of the Auger@TA Phase I study). Here, the same ≈ 11 m spacing between stations as used by Auger for doublet and triplet setups is used [14]. These standard Auger hexagon and triplet configurations were chosen to minimize reconstruction biases when using the fine-tuned reconstruction procedure developed for the Observatory.

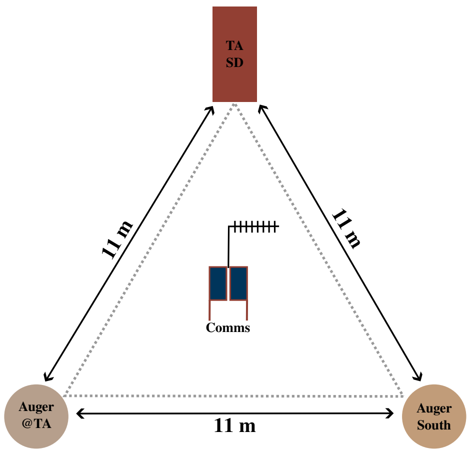

Figure 2: Schematic view of the central triplet. The central communications station is located at the center of micro-array and triplet, while the three stations are spread out evenly around it in an equilateral triangle with a side length of ≈ 11 m.

3.1 The Auger@TA station

The stations used to make up the micro-array hexagon, with the exception of the regular Auger station in the triplet, are prototypes that have been retro-fitted to more closely match a regular Auger station. A schematic overview of these retro-fitted stations, *Auger@TA* stations, can be seen in Figure 3.

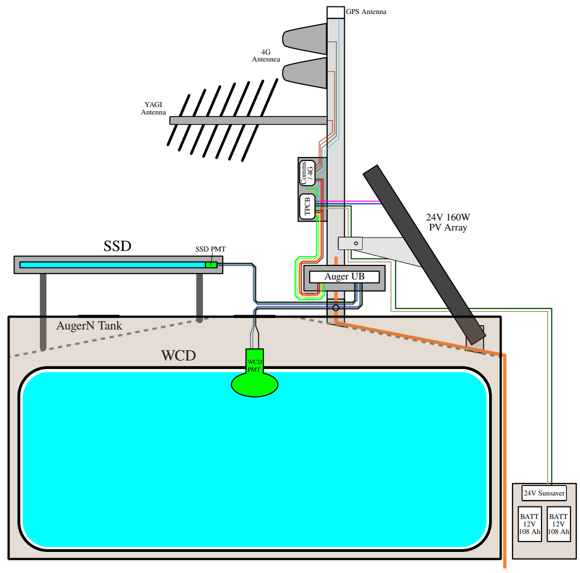

Figure 3: Schematic view of an Auger@TA station.

The Auger@TA station makes use of the 1-PMT prototype shell which has largely the same internal form factor as regular Auger tanks, but uses only one PMT at the center of the station instead of the usual 3-PMT configuration. The bases used with the PMTs have been replaced with regular Auger bases, and are connected to the typical Auger electronics of a Unified Boards (UB) and a Tank Power Control Board (TPCB) [1]. For the regular Auger station, these are placed under the so-called "dome". However, the 1-PMT prototype shells do not have such a structure, as their original electronics were designed to be installed directly inside the tanks. This required procuring of an alternative, which was found in the form of repurposed ammunition boxes hereafter referred to as E-kit boxes. They were chosen as they are water-tight and have a very similar form-factor to the UBs. The E-kit boxes have been painted with white liquid rubber RV roof coating to efficiently reflect sunlight and provide strong heat-protection. The UBs are mounted inside the E-kit boxes on removable drawer slides as this allows quick and easy access to the UB in the field and even makes replacing a board very straightforward. A picture of such an E-kit box with a UB inside can be seen in Figure 4.

For Auger@TA stations, the TPCB box had to be moved as well and is now located in a NEMA enclosure fitted to the communications mast of each station together with each stations' communications electronics. These boxes are also coated in white paint to reflect as much sunlight as possible. An example of such a box can also be seen in Figure 4. The solar power system was upgraded to 24 V/160 W/216 Ah in order to provide sufficient power for the station electronics and the communications system.

Figure 4: Auger@TA station components deployed in the field. Top left: Positioning of the E-kit and the NEMA box on the communications mast. The TPCB and a Raspberry Pi for the communications system can be seen. Top right: Communications mast with GPS (top), 4G (middle), and YAGI (bottom) antennas in place. Bottom left: Close-up of the NEMA enclosure. Bottom right: Inside view of the E-kit box with the UB on the drawer slides.

Additionally, thanks to the efforts of the Karlsruhe Institute of Technology, the Bergische Universität Wuppertal, and the Observatory in Malargüe, each Auger@TA station will also be outfitted with AugerPrime Surface Scintillator Detectors (SSDs) [15, 16] that were assembled with spare material. This includes eight SSDs, SSD support structures, SSD-to-UB connection cables, PMTs, and bases. These SSDs are an addition to the original scope of the micro-array and will provide interesting opportunities for additional cross-calibrations. All the cabling between the two boxes, the PMT hatch cover, the SSD enclosure, and the battery box, are routed through watertight conduits thus providing a completely weather- and dust-proof electronics system.

3.2 The Communications System

The communications system for the Auger@TA micro-array is completely custom-made, but uses readily available components and will be used to provide access to the stations directly via the internet.

Communication between stations located at the outside of the hexagonal array and the central triplet are accomplished with YAGI antennas using the Digi Xbee Pro transceiver operating at 900 MHz. An abstraction layer has been implemented that operates over the Xbee native serial line to provide internet access to all nodes at every station, even while science data and commands are relayed between stations via regular Auger communications protocols. This will allow communication with each station directly, for example for debugging purposes. Finally, communication from the central node to the outside world is accomplished via a 4G LTE (mobile) wireless modem. An example from a station in the field using both antenna types can be seen in Figure 4.

4 Micro-array Deployment

An area in the south-east corner of the TA array near Black Rock FD was chosen for the site of the micro-array. The chosen site has minimal overlap with land regulated by the US Bureau of Land Management (BLM), thus making a deployment via motorized vehicles (see Figure 5) possible for the Auger@TA effort.

Figure 5: Auger@TA station being put in place at its deployment site with an excavator.

The deployment of the micro-array took place over a span of two weeks at the end of September 2022, with the first week being focused on pre-deployment tasks such as the final assembly of the SSDs, decommissioning of the Phase I stations for re-deployment, liner inflation and inspection, etc. and the second week being used solely to deploy detector stations. The deployment site as well as the deployed triplet can be seen in Figure 6.

Table 1: Overview of deployment status for each station. Check-marks (green) denote accomplished items, while crosses (red) show which tasks are still open. "C" denotes central triplet stations. Unless specified, the station are Auger@TA stations. Station names inspired by [17].

Site	Station deployed	Components commiss.	Electronics deployed	SSD deployed
Sam (C)	✓	✓	✓	×
Gollum (3PMT, C)	✓	✓	✓	×
Frodo (TA, C)	✓	✓	×	×
Aragorn	✓	✓	✓	×
Arwen	✓	✓	×	×
Gimli	✓	✓	✓	×
Legolas	✓	✓	✓	×
Bilbo	✓	✓	✓	×
Galadriel	✓	✓	✓	×
Sauron (Comms)	✓	✓	✓	–

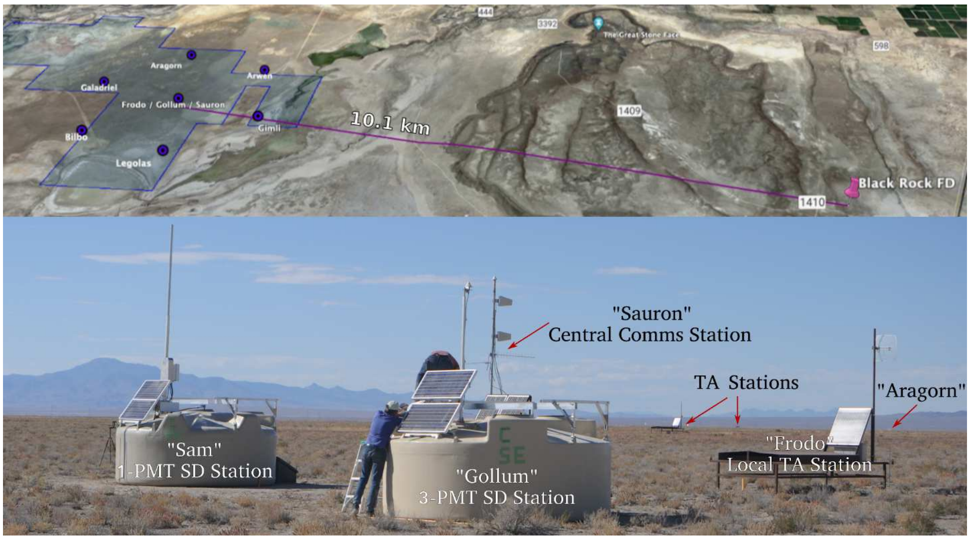

Figure 6: Top: Location of the 9 station micro-array within TA, also showing the distance to the Black Rock FD. Bottom: The center triplet and data acquisition comms station. The "Gollum" station is currently taking data with the 4G-connected "Sauron" central comms receiving event triggers. A communication link is established with "Aragorn" and "Galadriel" (not visible). Note the SSD support structure already installed on "Sam" and "Gollum". Station names inspired by [17].

In the weeks following the deployment, the water delivery to each station took place. As of today, all stations have been deployed in the field, with most stations only requiring PMTs (bases are currently being fabricated), SSDs, and communication systems (components backordered) to become operational. A fully instrumented micro-array is expected to be in the field by July 2023. An overview of the deployment status for each individual station is summarized in Table 1.

5 Expected Performance

In order to quantify the feasibility of obtaining each of the goals stated in section 1, and to gauge the expected performance of the Auger@TA Phase II micro-array, two sets of event simulations were produced: one set using the full regular Auger array (FA), and one with only a single hexagon (SH) of Auger@TA stations.

These simulations were produced using proton CORSIKA showers thrown with an E^{-1} spectrum in a range $E \in [18.0 - 19.0) \log_{10}(E/\mathrm{eV})$ (see Figure 9). To ensure maximum comparability between the two simulation sets, each CORSIKA shower was thrown at the same geometry, with the same random seeds in both detector configurations, and then matched at the event-by-event level. To avoid edge effects, a fiducial $5 \times 5\,\mathrm{km}^2$ area around the central hexagon was used in both cases which exceeds the triggering range of the SH configuration. The Auger $\overline{\text{Off}}\underline{\text{line}}$ framework was used with small adaptations made to the detector simulations in the case of the SH stations to reflect the changes that come with using Auger@TA stations.

5.1 Simulated Station Calibration

To adapt the Auger detector simulations to represent Auger@TA stations the following changes were made:

- Remove all PMTs but one;
- Move PMT to the center of the station;
- Set higher thresholds for single PMT triggers.

Additionally, studies of the station calibration, displayed in Figure 7, have shown that while the noise rate in the calibration histogram is slightly higher, the simulations only show a negligible difference in the relative response to air showers between the 1-PMT and 3-PMT configurations, lowering expected calibration uncertainties for Auger@TA results. Thus, for now the studies shown here use the same calibration constants as for regular Auger stations. However with more statistics and real calibration histograms from the deployed array, this study will be revisited in the future.

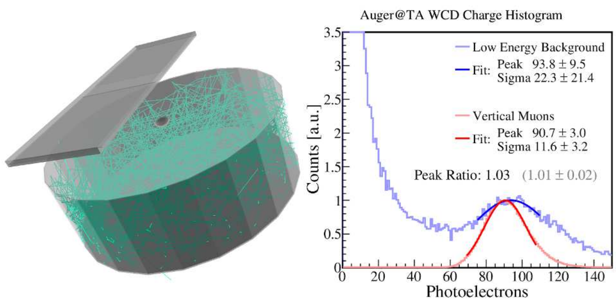

Figure 7: Full implementation of the Auger@TA stations in Geant4-based detector simulations. Left: Geant4 implementation of the 1-PMT Auger@TA detector configuration with SSD. Right: Simulated calibration histograms for the 1-PMT detector configuration.

5.2 Array-wide Simulations

A high-quality, high-precision energy reconstruction is a key element for the Auger@TA effort to be successful, but

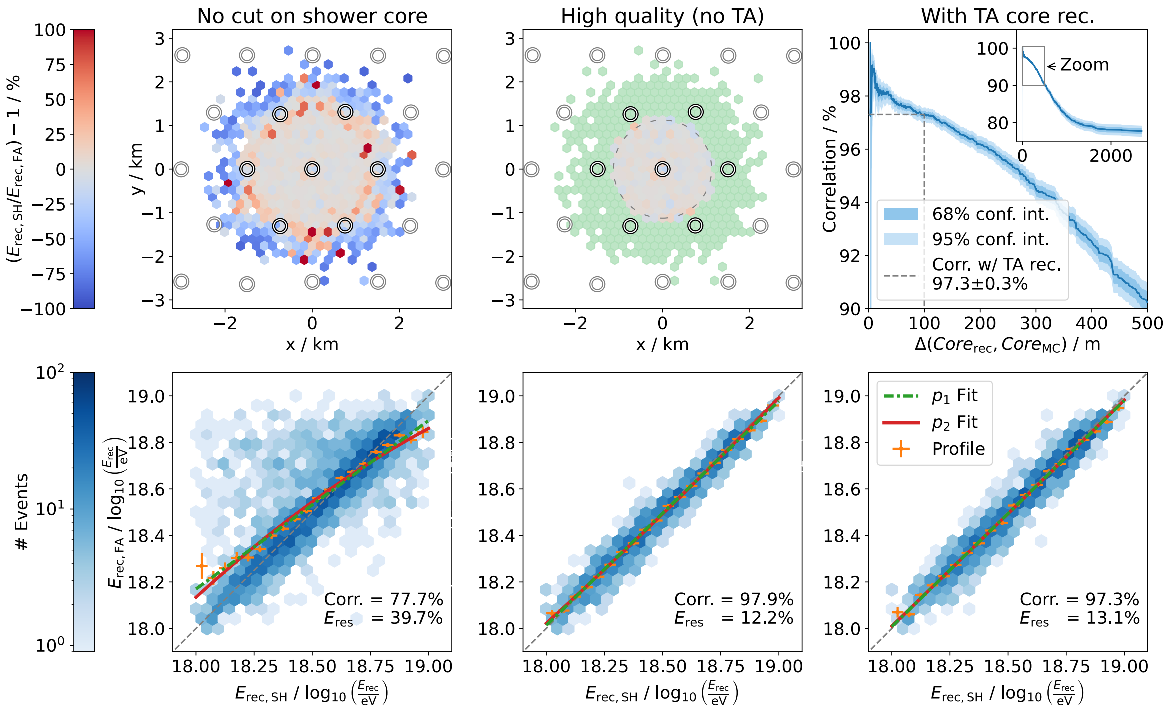

Figure 8: Expected energy reconstruction quality of Auger@TA phase II: Left panels: All reconstructed events from the self-triggered array. Center panels: High-quality reconstructed event sample. Right panels: Estimated reconstruction quality using a TA 100 m core reconstruction uncertainty (see text for details).

is hard to achieve with only one hexagon with 1-PMT stations. The energy reconstruction of the regular Auger array can be used to benchmark the performance of the single hexagon, and their reconstructed energy correlation is shown in Figure 8. When comparing all events that were successfully reconstructed in both simulation sets, the energy resolution of the single hexagon is rather poor with 39.7 % (see Figure 8 top left). This is to be expected since events that have a shower core falling within the single hexagon will have, on average, a better reconstruction. Events where the shower footprint is not contained in the hexagon or the shower core falls outside of the hexagon have a worse reconstruction in direct comparison with the full array simulation set. This can also be verified with the top left plot in Figure 8, which shows the energy reconstruction biases between the single hexagon and the full Auger SD array. A cut on the distance of the reconstructed shower core to the central station ($R_{\mathrm{center}} \leq 1125$ m) allows for the selection of high-quality events and is shown in the middle of Figure 8. As can be seen in the bottom middle of Figure 8, applying this cut to the simulated data significantly improves the energy correlation with the full array.

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. In most cases, however, the events detected by the Auger micro-array will also be observed by TA, and the TA shower core reconstruction can be used to inform the Auger reconstruction with minimum bias. This is studied in Figure 8 (right panels), by considering how the SH core reconstruction uncertainty affects the energy correlation between the SH and FA data sets. Assuming a TA shower core reconstruction accuracy of $\approx$ 100 m at low energies [13], this indicates that with the TA shower core reconstruction we could reach an energy resolution of 13.1 %, which is very similar to that of the high-quality cut (12.2 %).

5.3 Expected Event Rate and Outlook on Flux Comparison

The single hexagon simulation set can also be used to extract the expected trigger efficiency of the micro-array. By folding in the UHECR spectrum [18], an expected yearly event rate can be calculated and is shown in Figure 9.

By comparing the distribution of reconstructed energies (with and without quality cuts) to the thrown Monte Carlo distribution, a region where the reconstructed distributions are flat can be selected. This region ranges from $18.3 - 18.8 \log_{10}(E/\mathrm{eV})$ and is suitable for making a cosmic ray flux measurement to potentially investigate the nature of the 9 % energy scale difference shown in Figure 1. As illustrated in Figure 8, by using the TA core reconstruction, the majority of reconstructed events are expected to be usable for this measurement. This means an event rate of up to 65 events/yr in the chosen high-energy region can be obtained. At this rate, we expect to achieve an 8.7 % statistical uncertainty on our flux measurement after two years, potentially allowing us to make a 1 σ level comparison between Auger and TA flux measurements. A 7-year run-time will be needed to achieve a 2 σ level comparison unless lower energy events can eventually be incorporated in the flux measurement. Flux measurements made at lower energies would of course have better statistics, although the quantification of systematic uncertainties is still a work in progress. Refinements to the simulations are planned and likely to optimize the number of events that may be used for the flux comparison study.

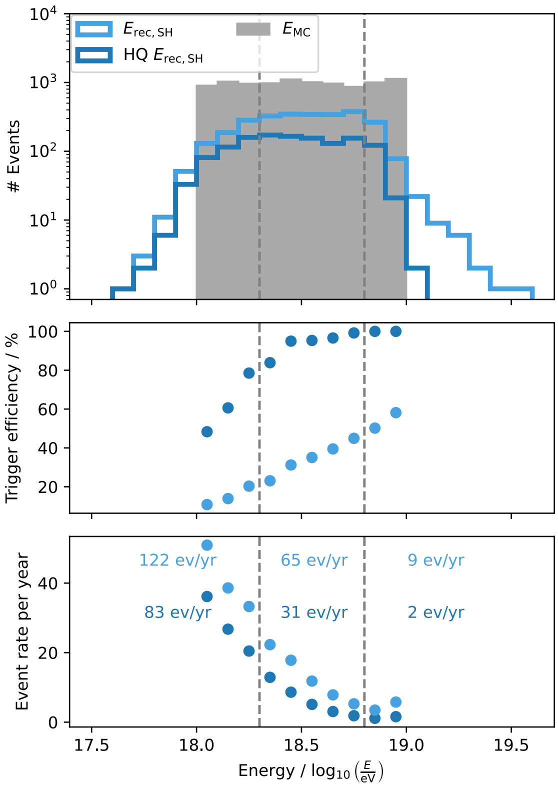

Figure 9: Expected trigger efficiencies and event rates for the Auger@TA micro-array from simulations. All plots: light blue: all reconstructed data, dark blue: high-quality selection (see Figure 8). Top: Reconstructed energy distributions in comparison to the energy distribution of thrown events (filled histogram). The dashed lines represent the energy region that is suitable for making a flux measurement due to trigger efficiencies. Middle: Expected trigger efficiencies. Full efficiency for the high-quality data set is reached at $10^{18.4}$ eV. Bottom: Expected event rate per year with event counts for the low energy, flux measurement, and high energy regions.

6 Summary and Outlook

The Auger@TA project is the only ongoing effort that can uncover discrepancies between the Auger and TA SDs using the exact same showers and, as such, is critical in assessing whether the observed discrepancies in the energy scales of the two experiments are due to astrophysical differences between the northern and southern UHECR skies, or due to as-of-yet unresolved discrepancies in how the two experiments analyze and interpret EAS data.

Phase I of the project has already provided promising results that will be published later this year. The second phase of the project is well under way, with the micro-array being deployed, nearing full instrumentation status with the first data likely being taken by the second half of 2023. In the field, one station is already fully up and running for testing purposes and on the communications side lossless transmission during multi-hour trials at a data rate of up to 9600 bps has been verified. These performance results are well within the required specifications to operate the full micro-array.

Currently, the possibility of adding another regular Auger station to form a second doublet of Auger-Auger@TA stations is being evaluated. As shown in subsection 5.3, the statistical budget for making a flux comparison is tight. Because of this, minimizing calibration uncertainties is important to study the compatibility, or lack thereof, of the TA and Auger reconstructions. These uncertainties can be lowered by adding a second 1-PMT/3-PMT doublet within the micro-array to lower systematic uncertainties coming from cross-calibrating two stations that each have their own inherent calibration uncertainties. A second 3-PMT station is already available at the Colorado School of Mines and could be deployed in the micro-array within the next year.

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