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Latest updates and results from the Fluorescence detector Array of Single-pixel Telescopes (FAST)

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The Fluorescence detector Array of Single-pixel Telescopes (FAST) is a next-generation cosmic ray experiment aiming to observe cosmic rays above $10^{19.5}$ eV with unprecedented statistics. To achieve this, FAST will utilise low-cost, easily deployable, autonomous fluorescence telescopes spread over a detecting area an order of magnitude larger than those of current observatories. We present the analysis of data taken by the current FAST prototypes in the northern and southern hemispheres between 2018 and 2024, including preliminary measurements of the energy spectrum and elongation rate from events observed in time coincidence with the Pierre Auger Observatory and Telescope Array experiment. We also briefly report on the development of the second-generation prototype telescopes and their scheduled installation as part of the FAST mini-array.

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1. The Fluorescence detector Array of Single-pixel Telescopes (FAST)

The origin of the universe's most energetic particles, ultra-high energy cosmic rays (UHECRs), is one of the largest open questions in modern astroparticle physics [1]. The Fluorescence detector Array of Single-pixel Telescopes (FAST) is one of several next-generation experiments aiming to elucidate these origins, in this case by focusing on the energy range above $10^{19.5}$ eV. The exceedingly low flux of UHECRs above this energy, roughly one particle per km^2 per decade, necessitates an enormous detection area to gather the required number of events for statistical analysis. FAST aims to achieve this by utilising an array of low cost, autonomous fluorescence telescopes observing the fluorescence light emitted from cosmic ray induced extensive air showers (EASs). Each telescope consists of a 1.6 m diameter segmented mirror which focuses fluorescence light onto a camera of just four 20 cm photomultiplier tubes (PMTs). A UV filter is placed at the aperture of each telescope to block photons with wavelengths > 400 nm. Accounting for the area of the camera box, the total area of the telescope aperture is 1 m^2 [2]. A full sized FAST array would be divided across both hemispheres, thereby allowing for observation of the entire UHECR sky using the same technology. At present there are four FAST prototype telescopes in operation. Three are located at the Telescope Array experiment (TA) in the northern hemisphere and one at the Pierre Auger Observatory (Auger) in the southern hemisphere. These installations are referred to as FAST@TA and FAST@Auger respectively. In this proceedings we report on the analysis of cosmic-ray events observed by FAST in time coincidence with TA/Auger. We also give a brief update on the status of the FAST mini-array.

2. FAST reconstruction procedure

Traditional reconstruction methods using fluorescence telescopes typically follow bottom-up procedures, where the signal and timing measurements from PMTs in a finely pixelated camera are fit to empirical functions to obtain the shower parameters [3, 4]. With only four PMTs in each telescope however, such an approach is not feasible with FAST. Instead, FAST opts for a top-down approach to reconstruction, where, for a given set of data traces, the telescope's response to many potential shower candidates is simulated and the best match found. This method, suitably called the "top-down reconstruction", is computationally expensive in comparison to bottom-up approaches and relies heavily on accurate knowledge of the detector response and surrounding conditions. The best fit shower parameters $\vec{a} = (\text{energy}, X_{\text{max}}, \text{zenith}, \text{azimuth}, \text{core}\, x, \text{core}\, y)$ are chosen by maximising the likelihood

$$\mathcal{L}\left(\vec{x}|\vec{a}\right) = \prod_{k}^{N_{\text{pix}}} \prod_{i}^{N_{\text{bins}}} P_k\left(x_i|\vec{a}\right) \tag{1}$$

where $\vec{x}$ is the observed data (PMT trace values) and $P_k\left(x_i|\vec{a}\right)$ is the probability of observing a signal x_i in time bin i of PMT k given $\vec{a}$. In practice we minimise $-2\ln(\mathcal{L})$ in ROOT using the Minuit2 minimiser. Successful minimisation of the likelihood requires a first guess of the parameters close to the true values [5]. In the following analysis, we will use the TA/Auger reconstructed values as a first guess. Work on developing a robust first guess method using only data obtained with FAST is ongoing.

	FAST@TA	**FAST@Auger**
Analysis period	2018/03 – 2018/10 (2018/10 – 2023/02)	2022/07 – 2022/10
Observation time	65 hrs (182 hrs)	122 hrs
Coincidence events	438	236

Table 1: Overview of the datasets used in the coincidence analysis. The FAST@TA column contains two values for both the analysis period and observation time. These correspond to the observation periods with two telescopes (left) and three telescopes (right, in brackets).

$X_{\max}$	EPOS-LHC ($500 - 1200\,\mathrm{g\,cm^{-2}}$)
Energy	E^{-1} ($1 - 100\,\mathrm{EeV}$)
Zenith	$\sin\theta\cos\theta$ ($0 - 80°$)
Azimuth	Uniform ($0 - 360°$)
Core position	Uniformly distributed inside circle (centred at (0,0), radius = 35 km)

Table 2: Parameter distributions used to generate the simulations for comparison with coincidence events. The right column shows the distributions sampled from and range (in brackets) for each parameter.

3. Coincidence data set and comparison with simulations

The data used in the following analysis was taken by FAST@TA and FAST@Auger using external triggers from their respective companion experiment i.e. TA/Auger. These triggers were provided by the fluorescence detectors at each experiment which overlook the same field of view as the FAST telescopes, these being the TA fluorescence detector at Black Rock Mesa and the Auger fluorescence detector at Los Leones respectively. For each recorded event (set of PMT traces), the following signal detection algorithm was used to determine if the event contained significant signal from an EAS. For each PMT, the original PMT trace is smoothed using a weighted moving average to give waveform N. Each time bin i in N is then analysed for signal by calculating the following ratio between signal and background,

$$R_{\mathrm{w}}(i) = \frac{N(i) - \overline{N_{\mathrm{BG}}}}{\max(N_{\mathrm{BG}}) - \min(N_{\mathrm{BG}})}. \tag{2}$$

Here, N_{BG} represents the background as calculated using a short section of N before bin i. If the maximum value of R_{w} over all PMT traces exceeds 2, then the event is labelled as an EAS candidate. With this method we have found 438 coincidence events in the FAST@TA data and 236 coincidence events in the FAST@Auger data. This information, together with the analysis periods and corresponding observation times of the coincidence event search, is summarised in Table 1.

Before reconstructing the data with our top-down reconstruction method, we compare the distributions of the coincidence event parameters as estimated by the TA/Auger monocular reconstructions with expected distributions estimated using the FAST simulation framework. The comparison is performed for events exceeding 1 EeV in energy. The parameters used to generate the simulations are listed in Table 2. Note that mass fractions of (H, He, CNO, Fe) = (0.25, 0.25, 0.25, 0.25) were used for generating $X_{\max}$. The results of the comparison are shown in Figure 1. To generate the simulated distribution for a single parameter, histograms of that parameter for showers

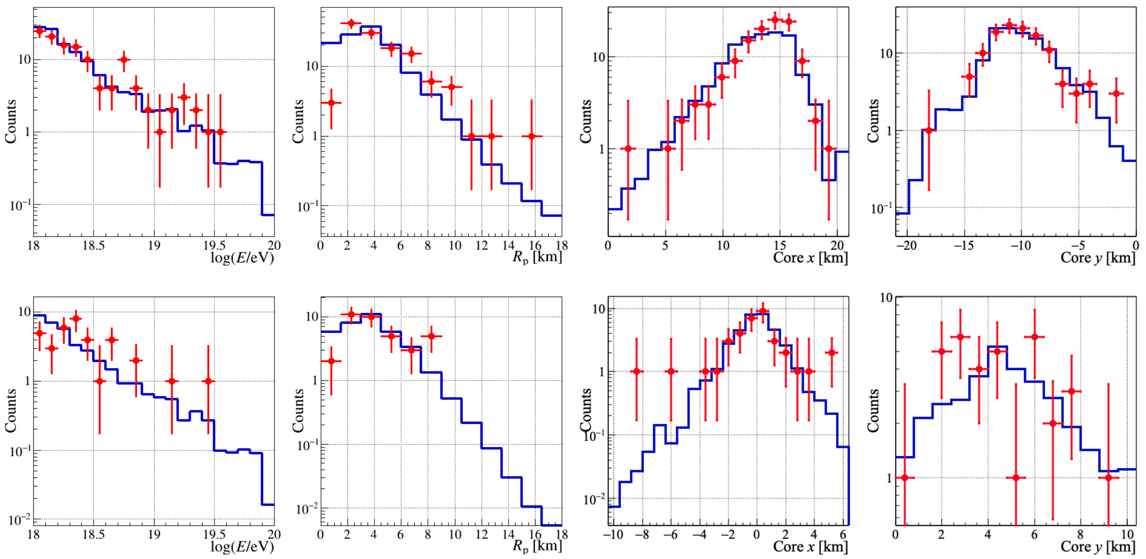

Figure 1: Comparison of coincidence event parameters (red points) as reconstructed by TA/Auger with expected distributions from FAST simulations (blue histograms). The FAST@TA (Auger) results are shown in the top (bottom) row. From left to right, the parameters compared are energy, distance to the shower axis R_{p} and core position (x and y).

"seen" by FAST were constructed in energy bins of width $\log(E/\mathrm{eV}) = 0.1$. These distributions were then normalised before taking their weighted sum, where the weights were equal to the number of expected showers in each energy bin given the observation time, simulation conditions and an assumed spectrum. We used the energy spectrum from TA as given in [6].

Ideally, when determining whether a simulated shower was "seen" by the FAST telescopes, the same selection process as used for coincidence events, i.e. TA/Auger trigger followed by passing the FAST signal search, would be applied. Unfortunately, replicating the TA/Auger trigger process is not feasible with the current simulation framework. Thus we adopted the condition that if a simulated shower had more than two PMTs with a maximum signal to noise ratio (SNR) > 6, it was considered equivalent to a coincidence event trigger. The definition of SNR here differs slightly from Equation 2, instead being identical to the formulation used by Auger in [7].

Exposures for the FAST@TA layout were calculated independently for the two telescope and three telescope configurations, with the appropriate observation time applied. These exposures were then added to calculate the final distributions. Also note that the simulated distributions have been scaled to match the area of the data histograms as at this stage the shape of the distributions is the primary concern. Overall, the shape of the distributions match reasonably well, suggesting that the telescope is largely performing as expected. Further work into improving the exposure calculation, in particular replicating the trigger process used to determine coincidence events, will be necessary for removing the need to scale the simulated histograms.

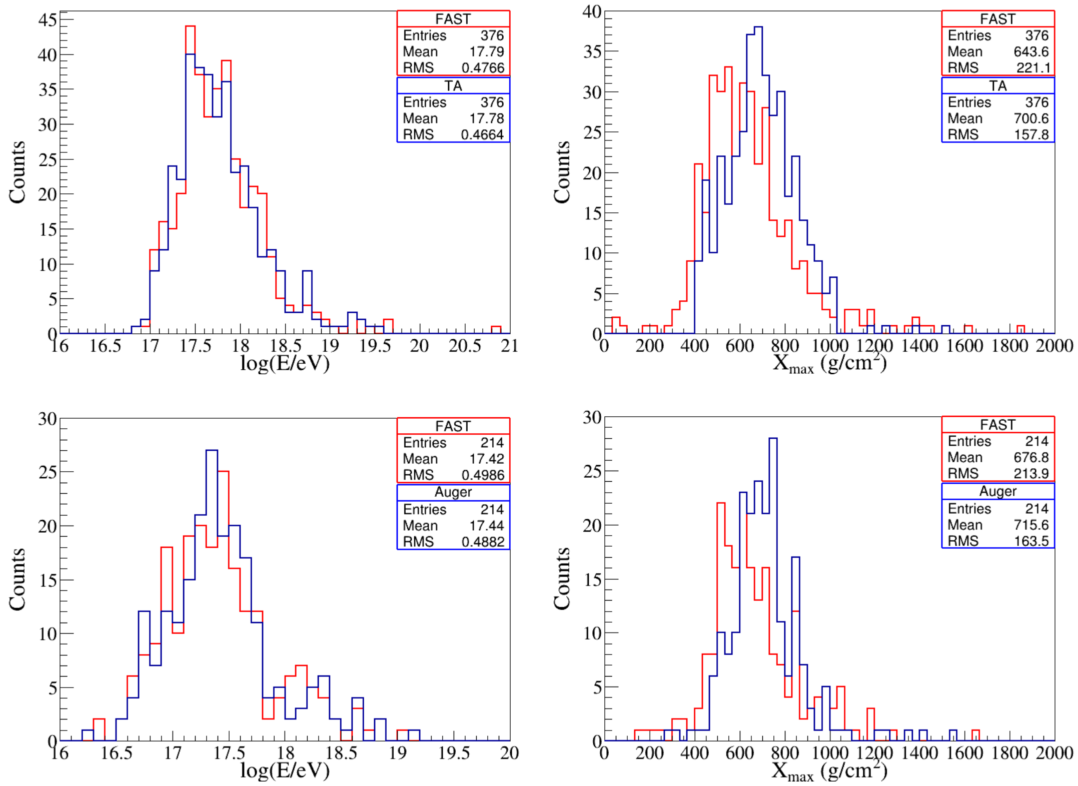

Figure 2: Histograms of the reconstructed energy (left) and X_{max} (right) values from FAST@TA (top) and FAST@Auger (bottom). The FAST results are shown in red. The TA/Auger results are shown in blue.

4. Reconstruction results

To reconstruct the coincidence events using the top-down reconstruction the following setup was used. First guess values for the minimisation were taken from the reconstructed values from TA/Auger, with all six shower parameters being reconstructed simultaneously. The cuts applied on the reconstruction results were that the minimisation was successful (as determined by the minimiser) and that the best fit time offset lay within an expected time window based on the known delay from the external triggers. Histograms showing the reconstructed X_{max} and energy distributions from FAST@TA and FAST@Auger in comparison with the TA/Auger results are shown in Figure 2.

There is a clear bias in the X_{max} reconstruction of FAST compared with both TA/Auger, approximately 60 and 40 g cm^{-2} lower respectively. Fundamentally, if the first guess values from TA/Auger are correct, or rather contain no inherent bias, then the FAST simulated traces based on these values should, on average, match the data traces. Hence the FAST reconstructed values should show no bias with respect to the TA/Auger values, assuming limited degeneracy in the top-down reconstruction. If degeneracy is present in the fitting process, then we would expect other parameters to also show a bias so as to compensate for the X_{max} shift. Checking the distributions of the other fitted parameters revealed no such clear bias, however further investigation into this point, possibly with an event by event analysis comparing the sets of reconstructed parameters, is planned for future

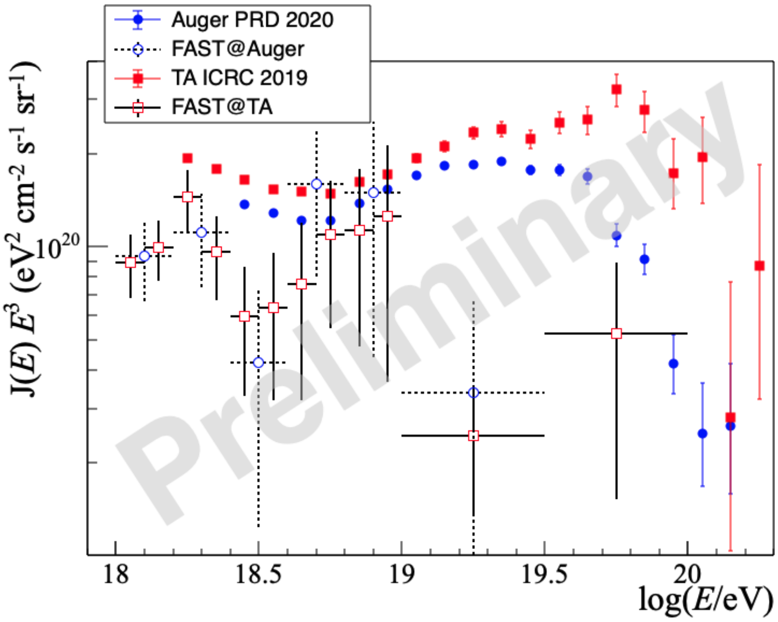

Figure 3: Energy spectra from FAST@TA and FAST@Auger estimated using 376 and 214 coincidence events respectively. Spectra from TA [9] and Auger [10] are shown for comparison.

work. Assuming the X_{max} bias is thus due to a systematic difference between the FAST data and first guess simulations using the TA/Auger parameters, the FAST simulation must not be accurately reproducing the real telescope/observation conditions. Possible sources of discrepancy between the simulation and reality include not accounting for degradation of the UV filter, not including night by night atmospheric conditions, and differences in the true and simulated PMT responses. Indeed, measurements taken of the FAST@TA PMTs' uniformity in early 2024 revealed unexpectedly high variation across the PMT surfaces. Work on integrating these measurements into the simulation and investigating their impact on the reconstructed values is underway. Small baseline fluctuations in the data traces may also cause increased fluctuations in event by event differences, however these are not expected to cause an overall bias in the reconstruction.

Putting aside the known bias, we have used the reconstruction of the coincidence events to calculate the first cosmic-ray energy spectra as measured by FAST. The results are shown in Figure 3. We also show the X_{max} elongation rate in Figure 4. We have plotted predictions from purely proton/iron showers using FAST simulations for comparison. The X_{max} values of the simulated showers were sampled from parameterisations of the EPOS-LHC distributions [8]. These showers were then reconstructed by a single FAST telescope using a first guess with geometry (zenith, azimuth, core location) fixed to the simulated values and X_{max}/energy randomly smeared from their true values by sampling from Gaussian distributions with means equal to the true values and widths of 30 gcm^{-2} and 10% respectively. Only showers with relative uncertainties in reconstructed X_{max} and energy < 0.5 were used in constructing the prediction rails.

In both the energy spectra and elongation rates the FAST@TA and FAST@Auger results generally agree within statistical uncertainty. Systematic uncertainties have not been estimated at this time. The shape of the FAST@TA and FAST@Auger energy spectra are broadly similar to the

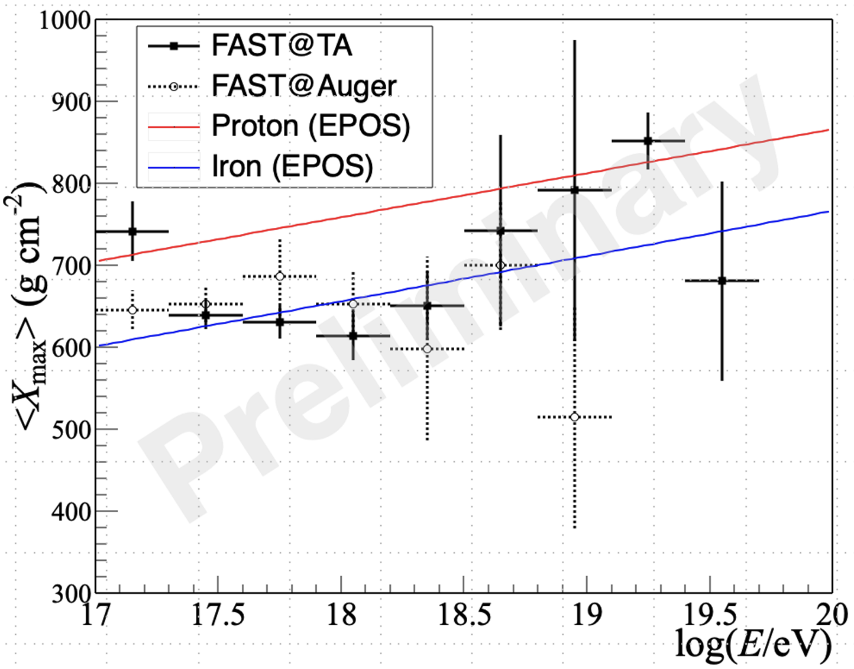

Figure 4: Average X_{max} as a function of energy (elongation rate) as estimated by FAST@TA (black circles) and FAST@Auger (open circles). The results are compared to the average reconstructed values of purely proton (red) and iron (blue) showers from simulations.

TA/Auger spectra, albeit with slightly lower absolute values. Further improvements to the exposure estimation and inclusion of additional reality in the simulations are expected to increase agreement between the results.

5. FAST mini-array updates

Over the next two years an additional four telescopes are planned to be installed at the FAST@Auger site forming a triangle with the existing telescopes. Known as the "FAST mini-array", the setup will allow for the first stereo observation of EASs with the FAST technology. The new prototypes to be used in this array are currently undergoing testing in the Czech Republic in Ondřejov, verifying the stand alone operation via solar powered battery and the new electronics. The prototypes will be deployed next to existing surface detectors at Auger, with site inspections having been completed in early 2024. Communications between the new prototypes in the field and the current telescopes at Los Leones will be handled by a long distance 5 GHz WiFi signal. The first set of two telescopes are planned to be installed in late 2025.

6. Summary

The Fluorescence detector Array of Single-pixel Telescopes is a promising candidate for a next-generation cosmic ray detector. With a new signal search method we have found more than 700 coincidence events across FAST@TA and FAST@Auger. Simulations of the FAST telescope appear to reproduce the shape of the data reasonably well at this early stage. Improvements in

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the exposure calculation will be necessary to match the total number of observed events. The first energy spectra and elongation rate results with FAST data have been presented. The results agree within statistical uncertainty across the TA and Auger installations. Finally, progress towards a FAST mini-array is ongoing, with the first set of telescopes planned to be installed in late 2025.

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