Detection of ultra-high-energy cosmic rays in the southern hemisphere with FAST: data acquisition and preliminary results

3th September 2025

Brief summary of the trigger paper

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1. Motivation
2. Algorithm definitions
3. Baseline generation and threshold calculation
4. Results: UHECR simulations
5. Results: UHECR events detected by FAST

Motivation

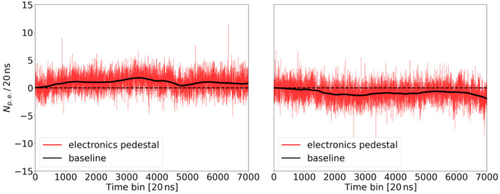


Figure 2. Examples of floating pedestals and their extracted baselines, recorded with the telescope shutter closed. The $x-$axis represents time, and the $y-$axis shows the number of photoelectrons per time bin. The baseline can either overestimate (left panel) or underestimate (right panel) a potential signal.

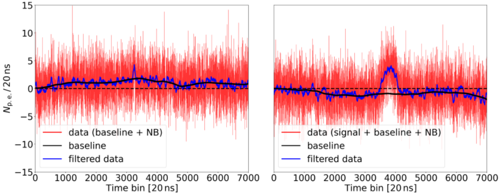
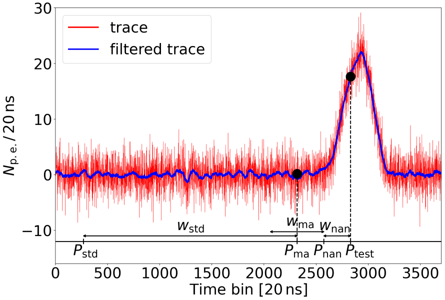


Figure 3. Left panel: The baseline combined with a NB, i.e., it does not contain a signal. Right panel: The baseline combined with a NB and a signal. The filtering process based on the Auger first-level trigger method is applied for both cases. Due to the floating baseline, the filtered data without a signal in the left panel reaches a higher maximum value ($\approx 4.30 N_{\text{p.e.}}/20\,\text{ns}$) than in the case when a signal is present in the right panel ($\approx 4.14 N_{\text{p.e.}}/20\,\text{ns}$).

Algorithm definitions



$$\mathrm{SNR}^{(1)}_{\text{inhouse}} = \frac{\text{trace}_{\text{FIR}}(P_{\text{test}}) - \text{trace}_{\text{mean}}(P_{\text{ma}})}{\sigma(\text{trace})\sqrt{\sum_{k=0}^{m-1} h_k^2}},$$

$$\mathrm{SNR}^{(2)}_{\text{inhouse}} = \frac{\text{trace}_{\text{MA}}(P_{\text{test}}) - \text{trace}_{\text{mean}}(P_{\text{ma}})}{\sigma(\text{trace})/\sqrt{m}},$$

$$\mathrm{SNR}^{(1)}_{\text{reference}} = \frac{\text{trace}_{\text{MA}}(P_{\text{test}})}{\sigma(\text{trace})/\sqrt{m}},$$

$$\mathrm{SNR}^{(2)}_{\text{reference}} = \frac{\text{trace}_{\text{MA}}(P_{\text{test}})}{\sigma(\text{trace}_{\text{filt}})}.$$

- inhouse algorithms: novel approaches for FAST
- reference algorithms: based on Auger/TA first level triggers

Baseline generation and threshold calculation

- 16,697,656 extracted baselines
- NB $= \mathcal{N}(\mu_{\mathrm{NB}}, \sigma^2_{\mathrm{NB}}) +$ baseline
  $\Rightarrow$ it realistically represents the behavior of the floating pedestal of a single PMT
- 1.25 Hz trigger rate for the NB per filter window and PMT
- various triggering algorithms across different levels of the noise background and filter lengths

Results: UHECR simulations

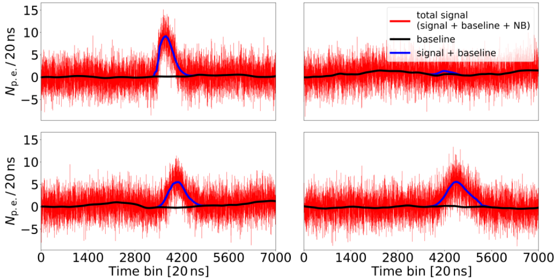
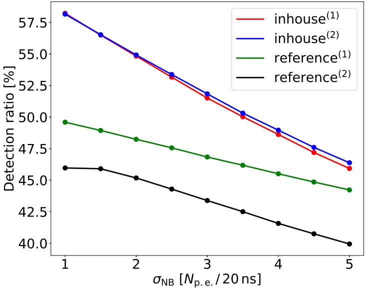


Figure 7. Example of a single simulated event for the FAST telescope consisting of four PMTs, generated using the following parameters: $E = 100\,\mathrm{EeV}$, $X_{\max} = 813\,\mathrm{g/cm^2}$, $\phi = -177^\circ$, $\theta = 52^\circ$, $x_{\mathrm{core}} = 4168\,\mathrm{m}$, and $y_{\mathrm{core}} = 18010\,\mathrm{m}$. The PMT layout reflects the sky view: the upper two PMTs observe elevations above 15°, while the lower two observe below 15°. The NB is drawn from $\mathcal{N}(\mu_{\mathrm{NB}}, \sigma^2_{\mathrm{NB}})$ with $\mu_{\mathrm{NB}} = 0$ and $\sigma_{\mathrm{NB}} = 2.5\,N_{\mathrm{p.e.}}/20\,\mathrm{ns}$. The final event, shown in red, includes the simulated signal, floating baseline, and the NB.

Results: UHECR simulations

- Analysis of 1.5 million UHECR simulations (834,973 useable) generated using FAST framework.
- Detection ratio of UHECR simulations as a function of σ_{NB} (standard deviation of the noise background).



- Both inhouse algorithms outperform the reference algorithm across all noise background levels.

Results: UHECR events detected by FAST

- FAST@Auger data between 4.7.2022 and 24.10.2022
- 1463 candidates in time coincidence with Auger

algorithm	strong signal $\geq$ 1 PMT	signal $\geq$ 2 PMTs	total
inhouse$^{(1)}$	209	60	269
inhouse$^{(2)}$	202	66	268
reference$^{(1)}$	139	24	163
reference$^{(2)}$	74	3	77

Table 3. Number of UHECR events detected by different triggering algorithms. “Strong signal $\geq$ 1 PMT” denotes events with at least one PMT exceeding 1.5 times the trigger threshold, while “signal $\geq$ 2 PMTs” requires two or more PMTs above the threshold, but none above 1.5 times the trigger threshold.

Results: UHECR events detected by FAST

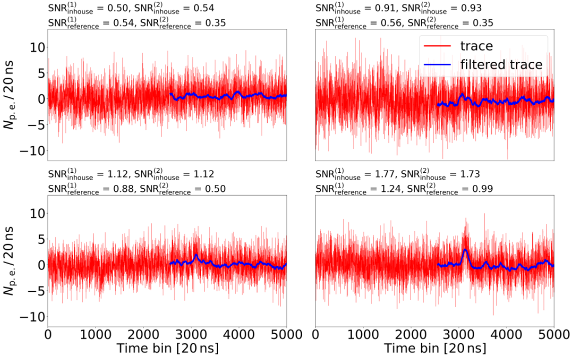
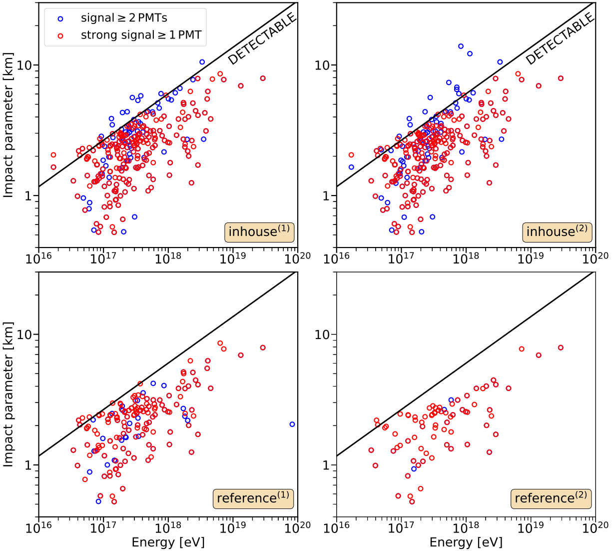
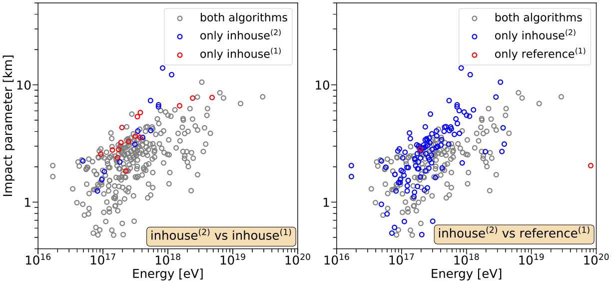


Figure 10. Example of a UHECR event classified as a strong signal by the in-house algorithms but not by the reference algorithms. The PMT layout reflects the sky view: the upper two PMTs observe elevations above 15°, while the lower two observe below 15°. The maximum normalized SNR values in each panel title illustrate the increased sensitivity to signals when using the in-house algorithms, particularly in the bottom PMTs.

Results: UHECR events detected by FAST



Results: UHECR events detected by FAST



Auger data

Acknowledgements

“The authors thank the Telescope Array and Pierre Auger Collaborations for productive discussions, and for providing logistical support and part of the instrumentation required to perform the FAST measurements in the field.”

What do we use in the trigger paper?

- Simulations: FAST framework (implemented as additional modules of the Auger Offline software framework)
  - Used in FAST papers: *Fujii et al. 2016*, *Malacari et al. 2020*
  - Not used but referencing in paper: *Mandát et al. 2017*
  - just mention FAST framework and cite *Malacari et al. 2020*
- UHECR events: time coincidence with Auger
- UHECR events: energy and radius given by Auger preliminary hybrid reconstruction (but only for FAST events with visible signal in FAST data)

We need to submit the trigger paper to Auger PC regardless of data used.

Various alternatives

1. **Complete manuscript as it is**

Advantages:

- $E - R_p$ graphs show nice results
- Preliminary comparison between FAST@TA and FAST@Auger

Disadvantages:

- None.

Additional information:

- We can refer to Fraser's thesis, as he has used all the data we included in the manuscript – discussed with Toshi and Fraser.

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Reconstructed parameters are obtained from
the Auger preliminary hybrid reconstruction
available in \cite{Bradfield2025}.
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- In principle, data are (will be) available so we can use them
- In *Malacari et al. 2020* $E - R_p$ graphs with TA monocular reconstruction data

Different alternatives

2. **Remove $E - R_p$ graphs**

   Advantages:

   - Not using reconstructed energy and radius from Auger
   - Using only GPS time information for coincidence events
   - Summary of detected events and example(s) remain

   Disadvantages:

   - Losing nice results and comparison between FAST@TA and FAST@Auger.

Different alternatives

3. **Remove $E-R_p$ graphs but perform our own reconstruction**

   Advantages:

   - The same as option 2 but something more
   - Reconstructed energy and radius from Auger used only as first estimation $\Rightarrow$ data from Auger would not be presented in the paper.

   Disadvantages:

   - FAST mono-reconstruction can be performed only for significant signals and even in this case, it contains huge uncertainty $\Rightarrow E-R_p$ graphs would not be beneficial.
   - Losing nice results and comparison between FAST@TA and FAST@Auger.

Different alternatives

4. **Removing the section "UHECR events detected by FAST"**

   Advantages:

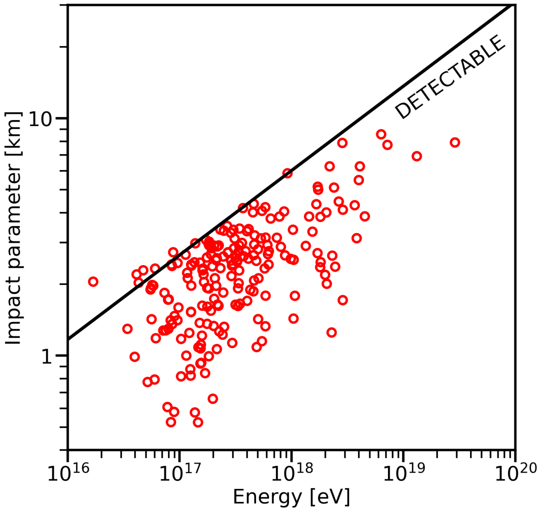
   - Auger PC cannot "say anything"
   - Only FAST framework used for simulations

   Disadvantages:

   - Based only on simulations; no real data presented $\Rightarrow$ boring!

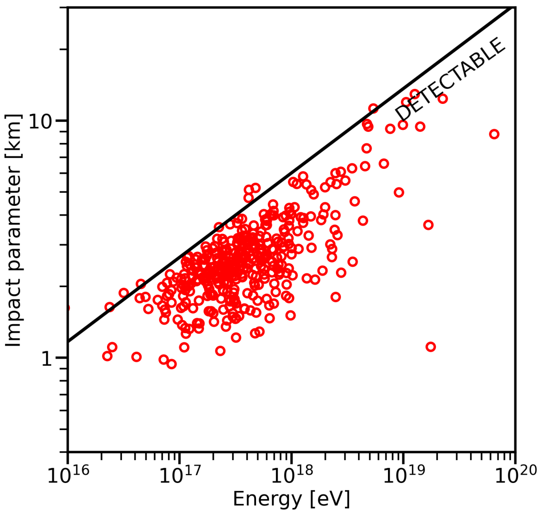
Update of $E - R_p$ graph (not presented in the paper)

Time period: 3.7.2022 – 25.10.2022



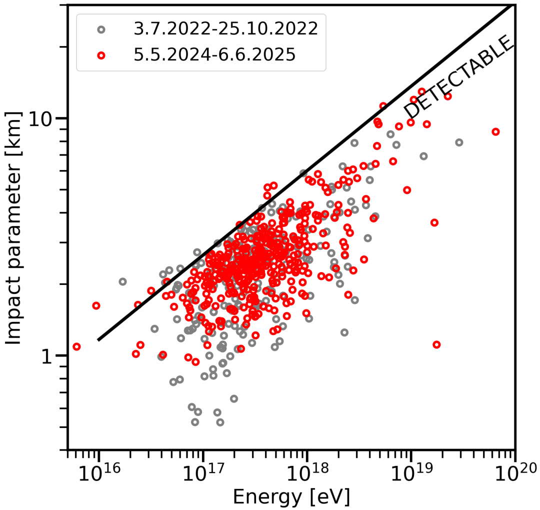
- Total of 202 "strong" signals

Time period: 5.5.2024 – 6.6.2025



- Total of 370 “strong” signals
- $\log(E) = 19.101\,\mathrm{eV}$, $R_p = 12.951\,\mathrm{km}$
- $\log(E) = 19.812\,\mathrm{eV}$, $R_p = 8.776\,\mathrm{km}$
- Previously no candidates at higher energies below detectable line.

Comparison



- Total of 572 “strong” signals