Fluorescence detector Array of Single-pixel Telescopes

Palacký University Olomouc

Ultra-high-energy cosmic ray detection using next-generation prototypes of the Fluorescence detector Array of Single-pixel Telescopes in both hemispheres

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on behalf of the **FAST collaboration**

https://www.fast-project.org/

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MINISTRY OF EDUCATION, YOUTH AND SPORTS

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Project motivation

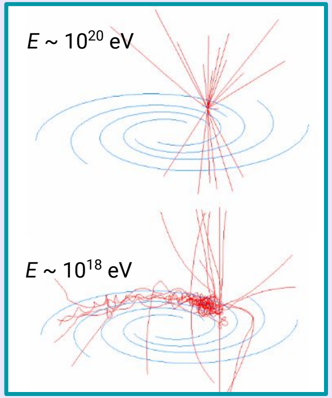
To clarify the origin of the acceleration of ultra-high-energy cosmic rays (**UHECRs**)

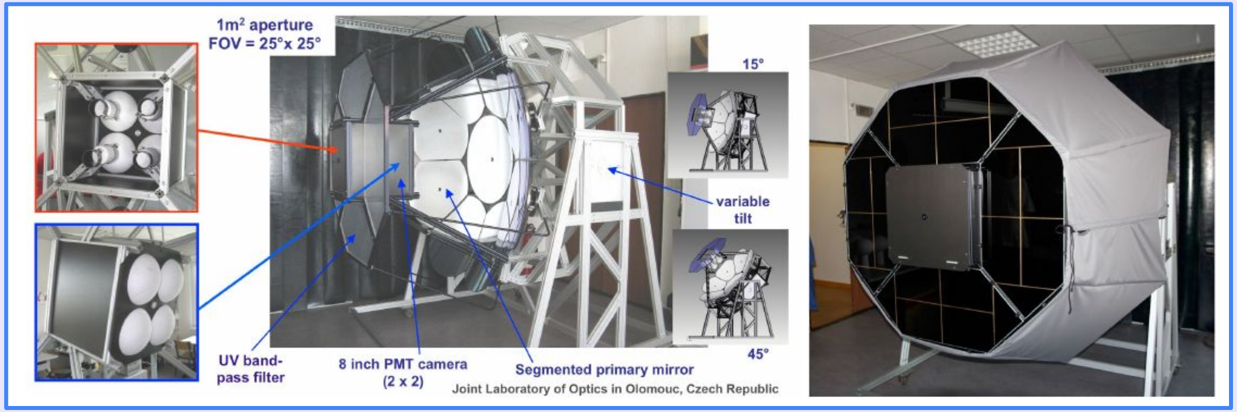
Target $E > 10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma ray

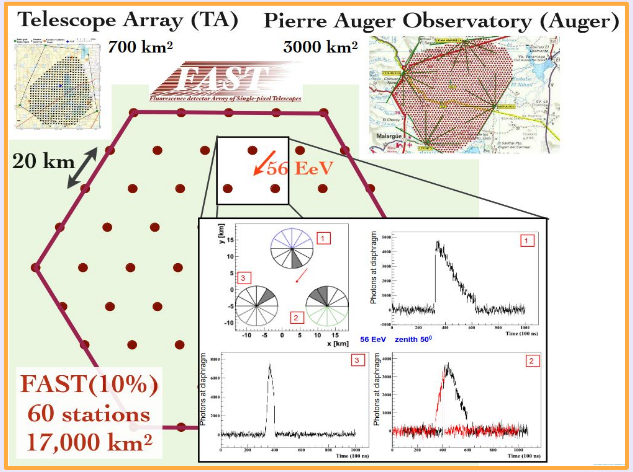
Next-generation of UHECR observatories: Low-cost fluorescence telescope array

Unified technology on both Earth hemispheres

Huge target volume ⇒ Fluorescence detector array







FAST prototypes

3 telescopes at BRM, TA, Utah (installed 2016, 2017 and 2018)
2 telescopes (1 in operation) at LL, PAO, Argentina (installed 2019 and 2022)

Coverage: ca. 80% FoV of TA FD, ca. 17% FoV of Auger FD

Synchronized operation with **external trigger** from the observatories

Remote control operation


FAST at Telescope Array


FAST at Auger Observatory

Towards the FAST mini array - location at PAO

stereo observation

allows independent EAS reconstruction

first phase - for testing purpose

installing two new telescopes (in 2025)

distance ~10 km to FAST at Los Leones

more signal statistics event of lower energies

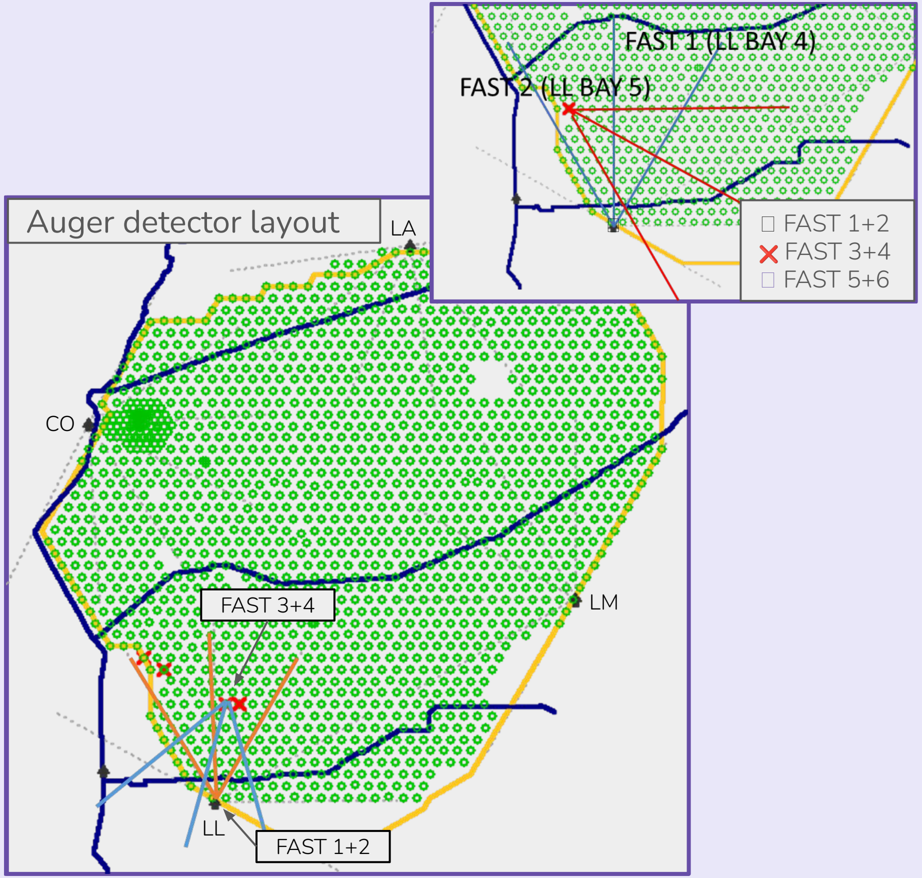
second phase

towards triangular array

with distance ~17 km

in total 6 FAST telescopes

focusing on $E > 10^{19.5}$ eV



FAST mini array - second-generation prototype

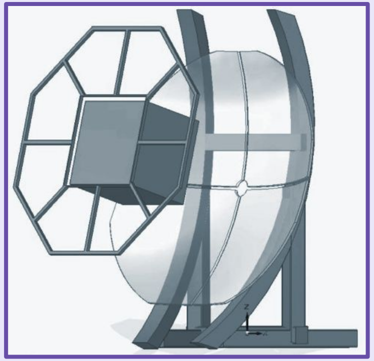
mirrors

- 9 → 4 segments
- simplified production
- hot slumping

new enclosure

- easier maintenance and transport
- fully autonomous
- solar system, sensors, electronics incl.
- water/moisture proof
- thermally insulated

safety curtain for fail-safe



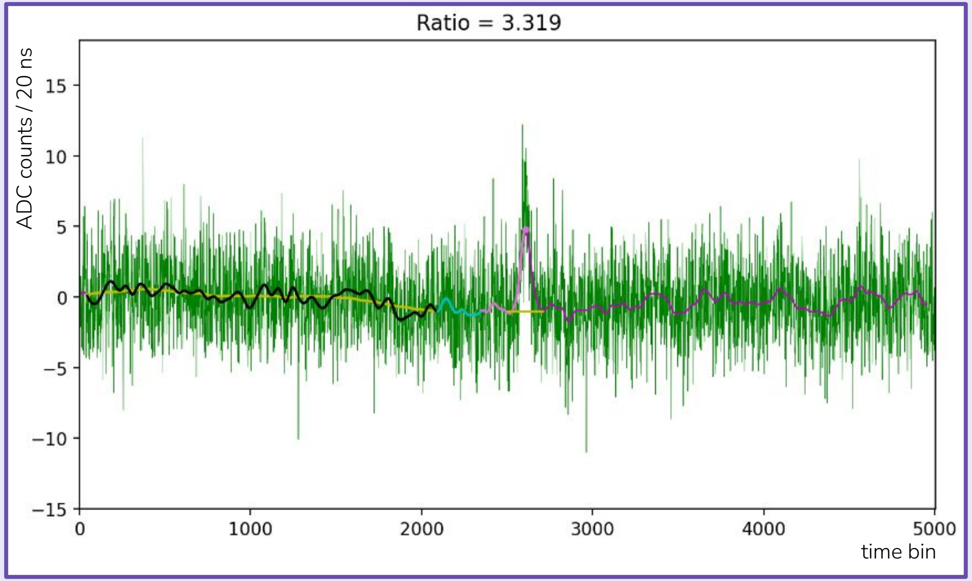
Signal search algorithm

Smoothing the waveform with a weighted moving average

Calculating weighted signal ratio for each bin $ratio_w = \frac{value(bin) - mean(noise)}{max(noise) - min(noise)}$

where **noise** is a given range of bins before the selected **bin**

Waveform has a signal if max($ratio_w$) > 2



Using this search algorithm, we found

FAST@Auger

197 coincidences (3 events with $E > 10^{19}$ eV)

FAST@TA

438 coincidences (10 events with $E > 10^{19}$ eV)

Signal quality comparison of FAST in both hemispheres

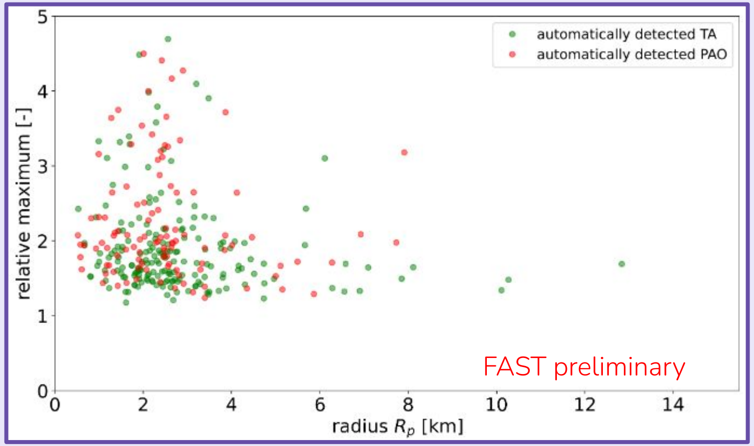
External signal triggering at both TA and Auger

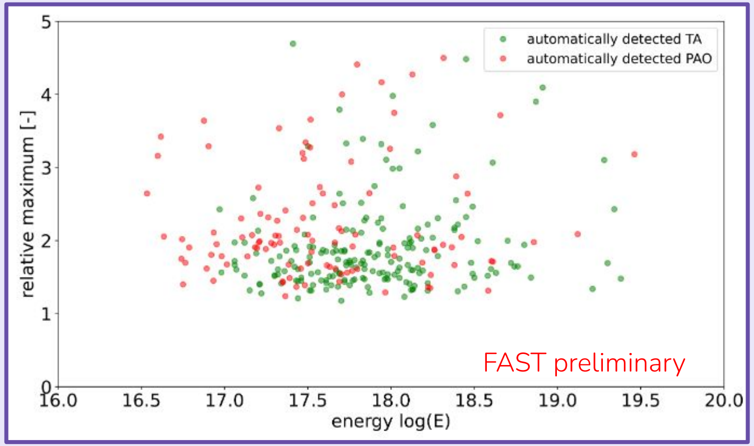
Relative maximum is defined as the size of the entire signal relative to the background

Illustrated in terms of the impact factor (R_p) and energy (E)

Good agreement in FAST telescope sensitivity across both hemispheres (~ 15%)

median values	$E < 10^{18}$ eV	$E \geq 10^{18}$ eV	R_p
FAST@TA	1.701	1.886	1.720
FAST@PAO	2.032	1.943	2.000



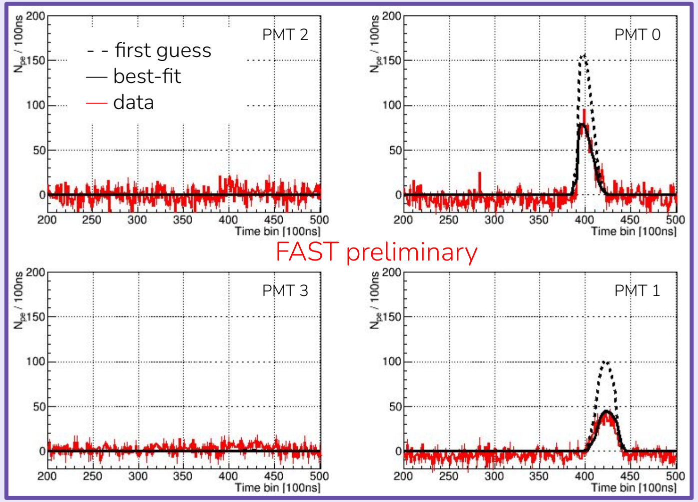


Event reconstruction

Top-Down Approach

Direct comparison of EAS detected by a telescope camera with EAS simulated using a full-event Monte Carlo simulation

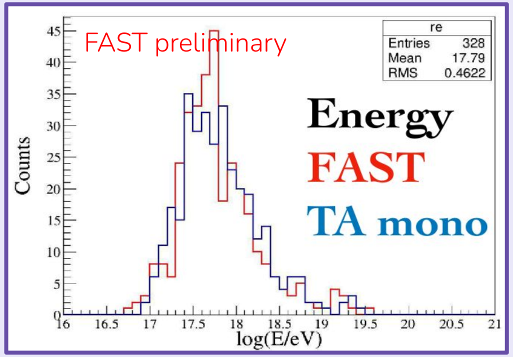
Maximizing $\ln \mathcal{L}(\vec{x}|\vec{a}) = \sum_{k}^{N_{\text{pix}}} \sum_{i}^{N_{\text{bins}}} P_k(x_i|\vec{a})$

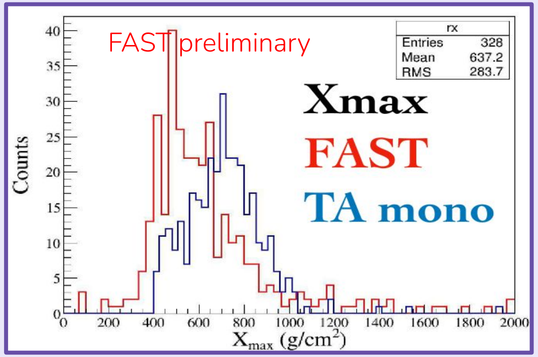


Reconstruction Details

Geometry, X_{max}, and E

Using TA mono-reconstructed geometry as initial guess





Key Objectives

Understand the bias on X_{max}

Study quality cuts

Machine learning with FAST

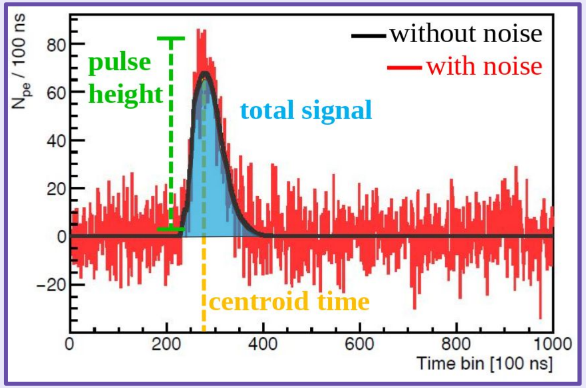
Input layer

signal characterization: pulse height, centroid time, total signal

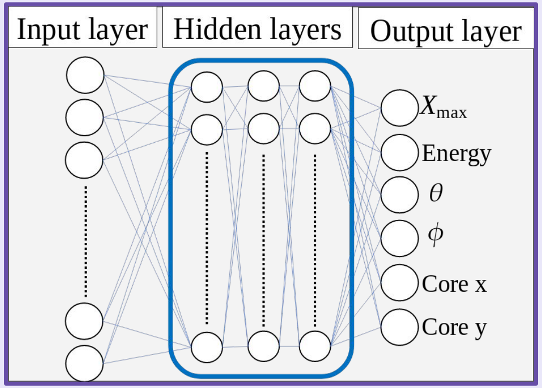
4x3 inputs for each telescope

Output layer

six outputs in total (X_{max}, E, $\boldsymbol{\phi}$, $\boldsymbol{\theta}$, core x, core y)

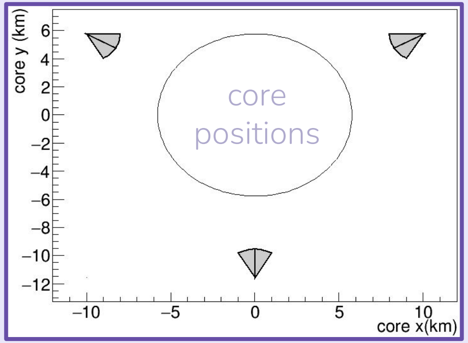


From each PMT with SNR > 5σ



Deep neural network (NN)

Machine learning for FAST mini array



Training: 300,000 showers

- X_{max} 500 - 1200 g cm^{-2}
- E 1 - 100 EeV
- θ 0 - 80°
- ϕ 0 - 360°

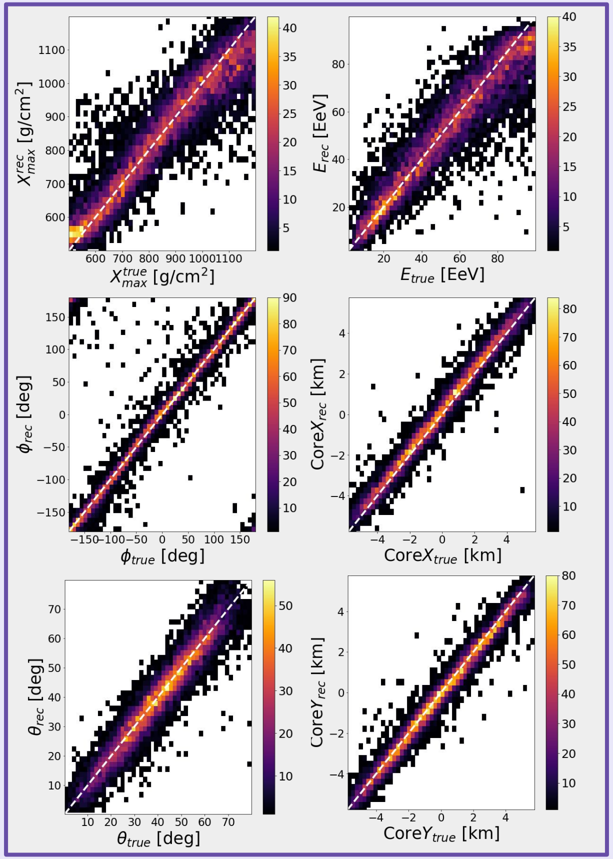
Testing: 10,000 showers

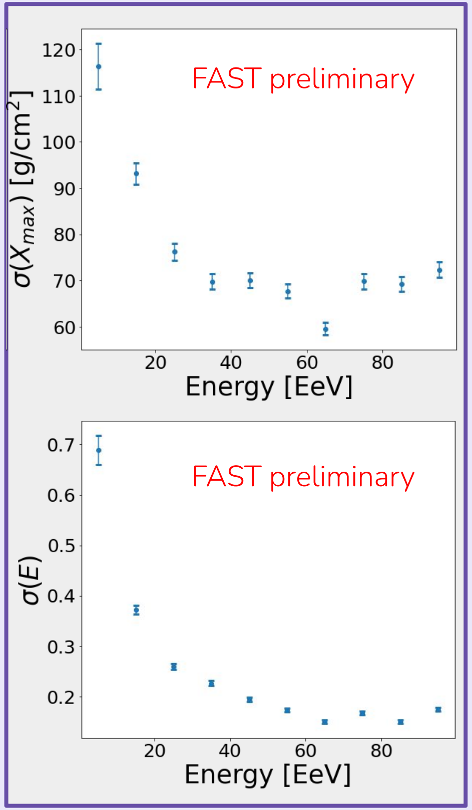
Layer structure: 72/72/36/18/6

Core pos: (0,0) with r = 5773 m

Reco cuts: $E > 10^{18}$ eV

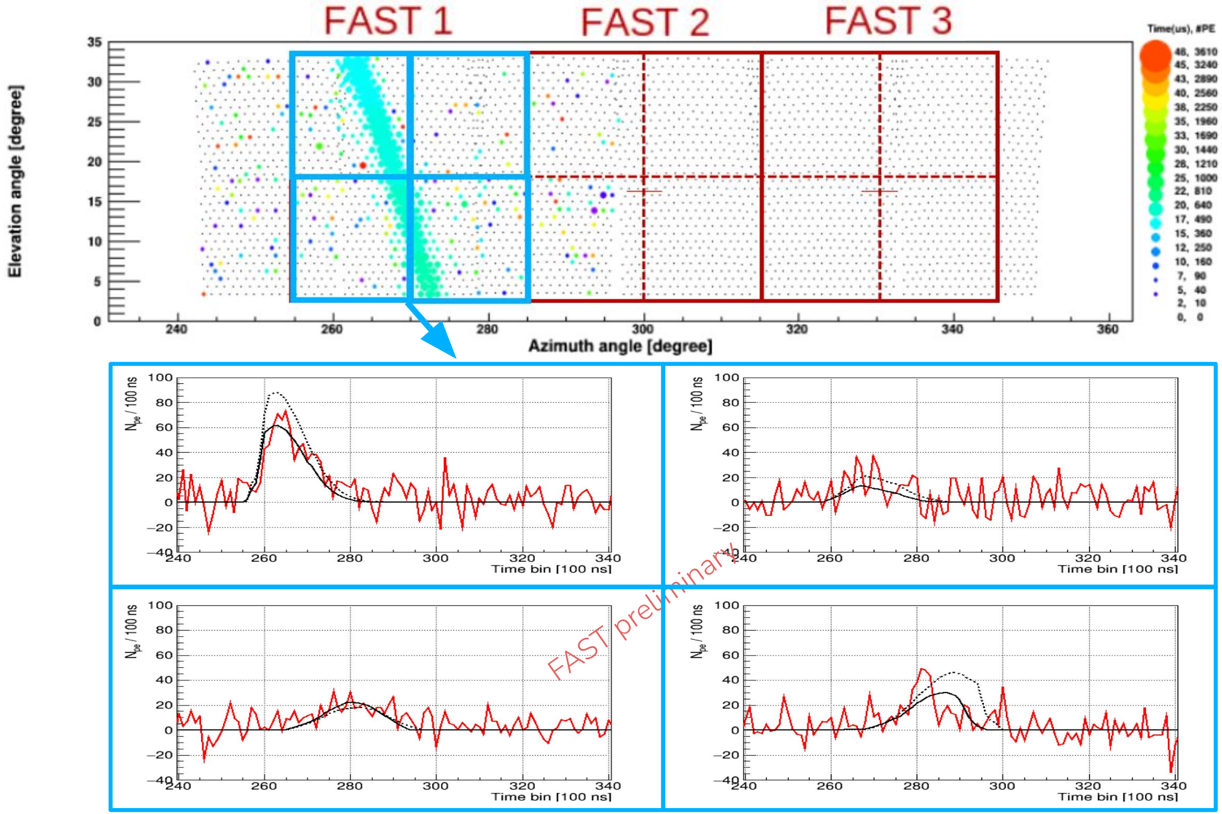
all three locations triggered

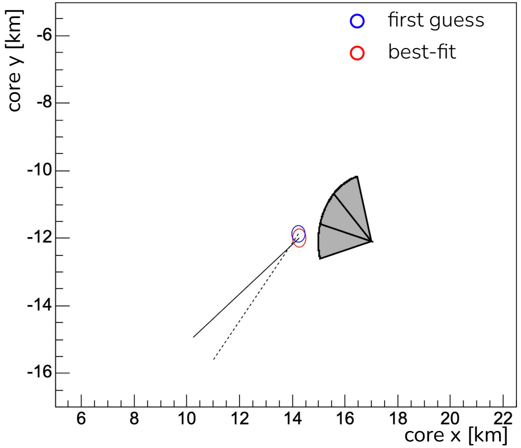




FAST event examples - from Telescope Array

Reconstructed values from TA used as first guess for the FAST reconstruction





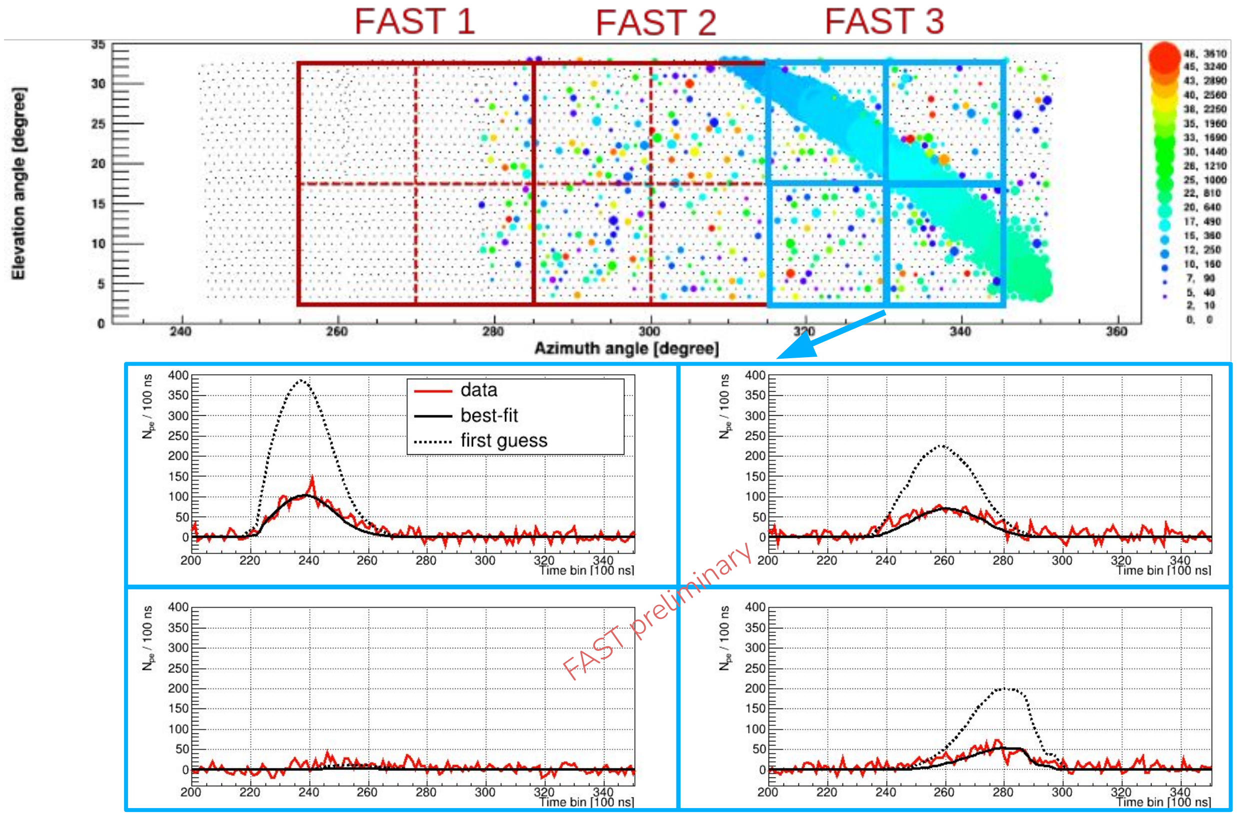
Preliminary result

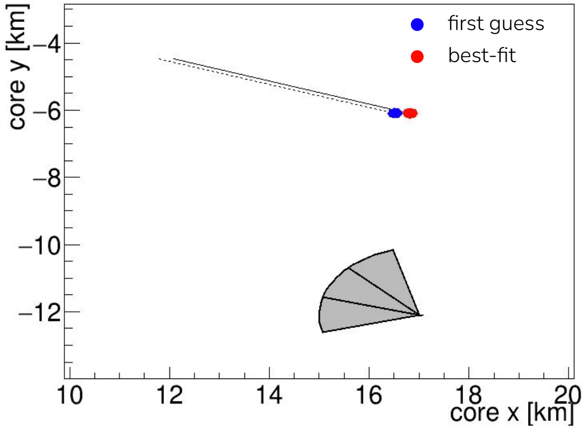
Event: 2019/01/11 06:30:01

	TA-Mono	FAST
Energy [EeV]	0.93	0.56 ± 0.11
X_{max} [g/cm^2]	663	764 ± 124
Zenith [deg]	20.4	20.5 ± 0.2
Azimuth [deg]	-138.8	-126.4 ± 1.8
Core x [m]	14240	14266 ± 19
Core y [m]	11880	11984 ± 37

FAST event examples - from Telescope Array

Reconstructed values from TA used as first guess for the FAST reconstruction





Preliminary result

Event: 2023/02/20 10:13:07

	TA-Mono	FAST
Energy [EeV]	21.9	6.1 ± 0.3
X_{max} [g/cm^2]	817	879 ± 41
Zenith [deg]	49.9	52.0 ± 1.6
Azimuth [deg]	-71.2	-71.1 ± 0.04
Core x [m]	16520	16821 ± 171
Core y [m]	-6090	-6095 ± 3

Conclusion

FAST aims for low-cost detection at $E > 10^{19.5}$ eV

Same technique on both Earth hemispheres

Exploring potential applications of neural networks

FAST future

- stereo observation
- independent reconstruction capabilities

Thank you

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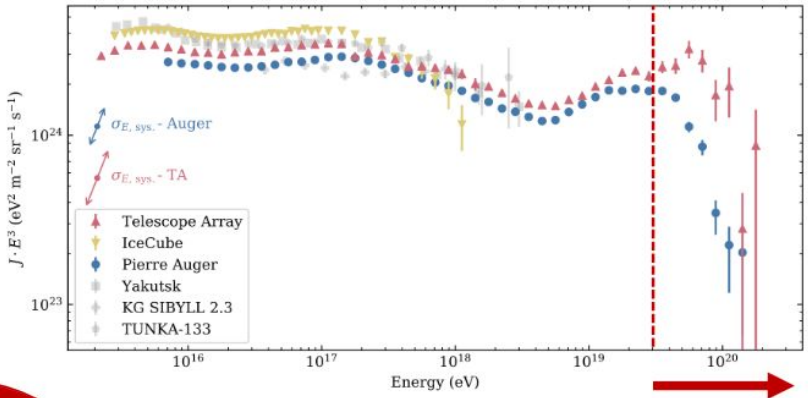
backup

Fluorescence detector **A**rray of **S**ingle-pixel **T**elescopes

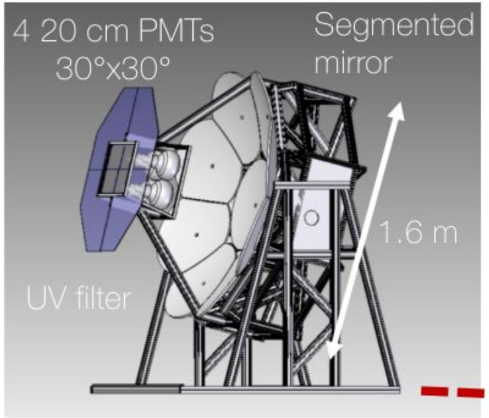
Goal:

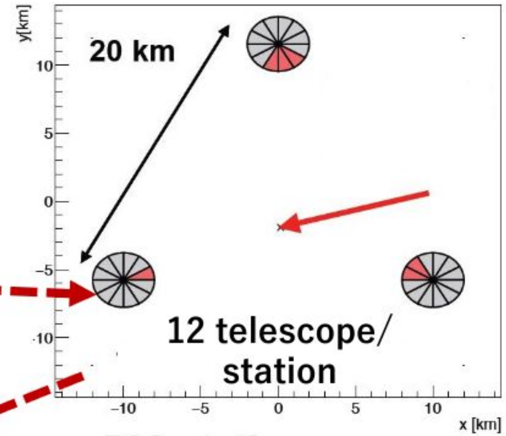
- Observe UHECRs with the same detector in both hemispheres
- Detection area - 150,000km^2

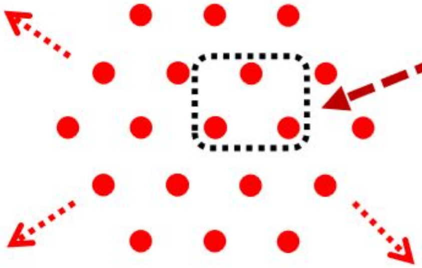


Aiming for 100% trigger efficiency above $10^{19.5}$eV

Design: Simplified, low-cost, easily deployable fluorescence telescopes







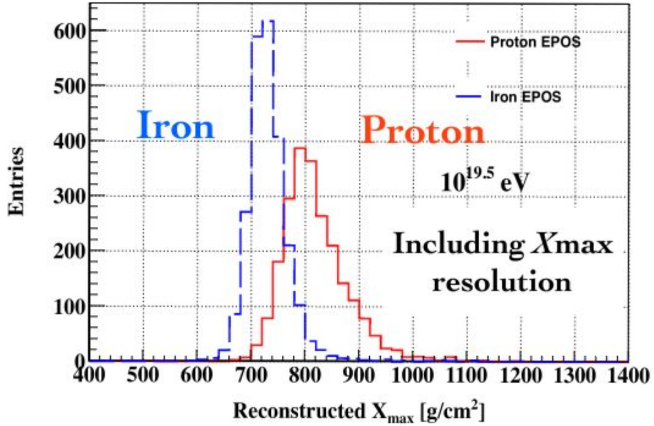
Current prototypes

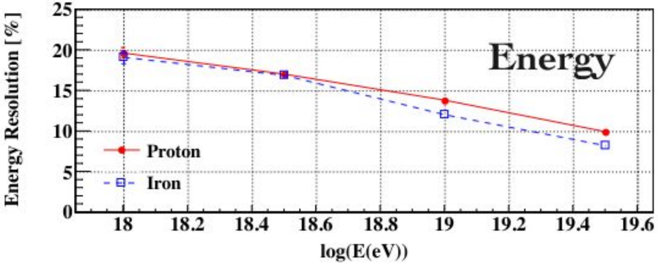
FAST@TA - 3 tel.

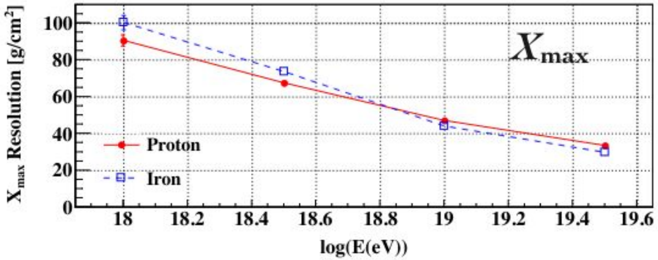
FAST@Auger – 2 tel.

Application of the FAST prototypes

- Install the FAST prototypes at Auger and TA for a study of systematic uncertainties and a cross calibration.
- Profile reconstruction with geometry given by surface detector array (1° in direction, 100 m in core location).
  - Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
  - Independent check of **Energy and** $X_{\mathbf{max}}$ scale between Auger and TA

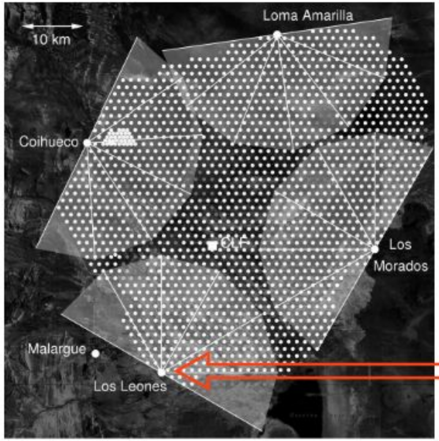






T. Fujii et al., Astropart.Phys., *74*, pp64-72 (2016)

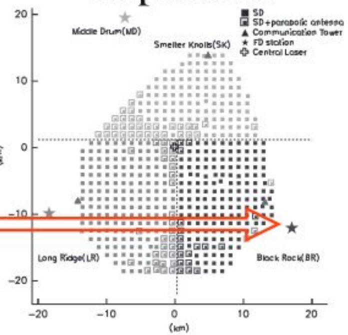
Pierre Auger Observatory



Auger collab., NIM-A (2010)

Identical simplified FD

Telescope Array Experiment

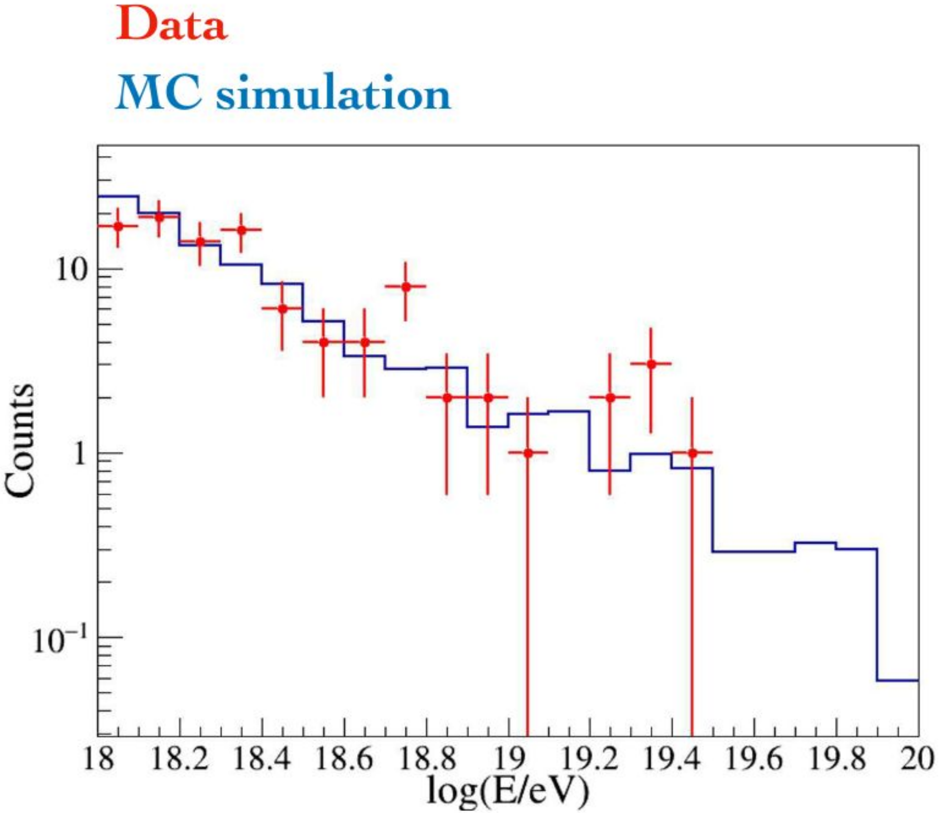


TA collab., NIM-A (2012)

Fluorescence detector Array of Single-pixel Telescopes

Data analysis of FAST@TA

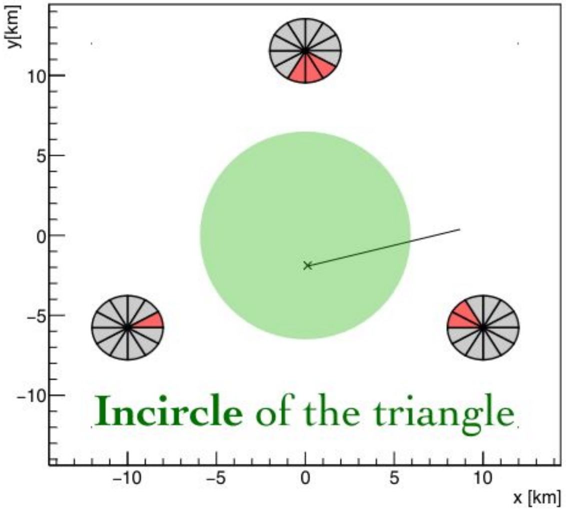
Work: Fraser Bradfield

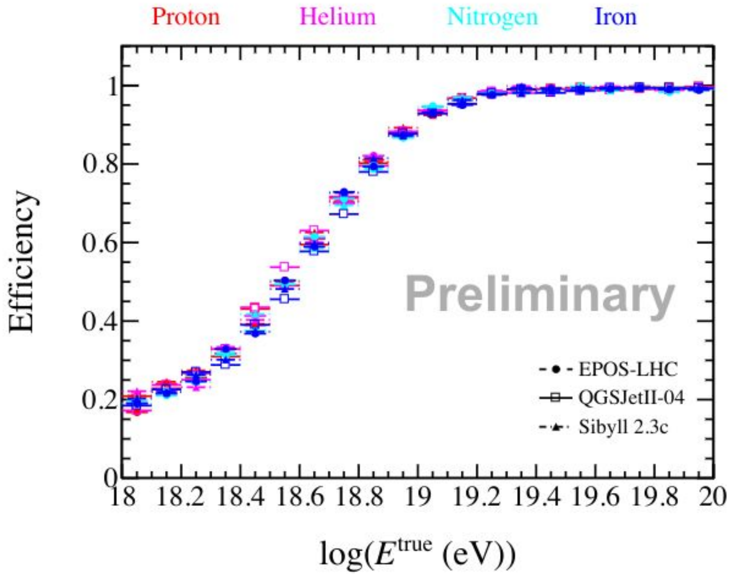


- Period: 2018/03/19 - 2023/02/25
- **Significant signal events with FAST** in the TA monocular reconstructed events
  - Total 336 events (**102 events above 10^{18} eV**)
  - Expected distributions estimated from **FAST detector Monte Carlo (MC) simulation**
  - Trigger condition: **>2 PMTs with S/N>6**
- **Data parameters are TA monocular reconstructed results**
  - Histogram of MC simulation was rescaled to be the same area of the Data

First guess reconstruction with a FAST array

- **Training data**: Energy of 1 - 100 EeV, $X_{\max}$ of 500 - 1200 g/cm^2, **uniform**
  - Night sky background: σ=10 p.e./100 ns, based on **field measurements at TA and Auger sites**
- **Test data:** $X_{\max}$ distributions based on CORSIKA-Conex simulations
  - 4 species (P, He, N, Fe) with 3 interaction models (EPOS-LHC, QGSJetII-04, Sibyll 2.3c)





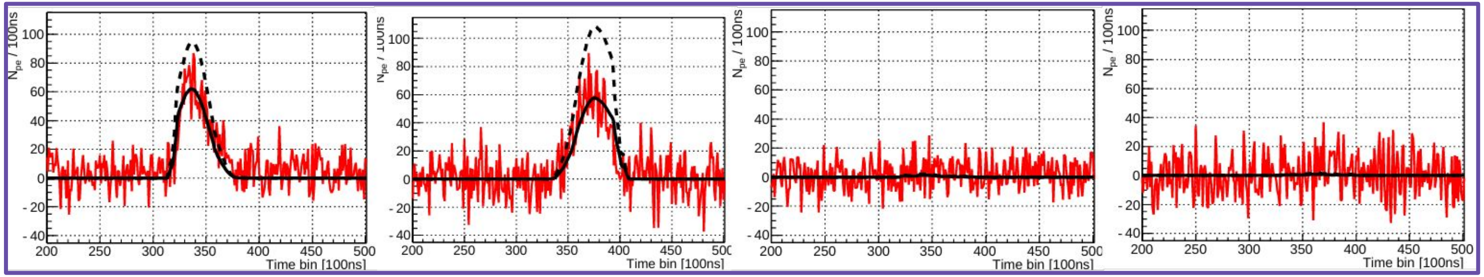
$$\epsilon = \frac{N_i(E^{\text{true}}_{\text{trigger}})}{N_i(E^{\text{true}}_{\text{thrown}})}$$

3-fold trigger efficiency

100% above 20 EeV

FAST event examples - from Telescope Array

Reconstructed values from TA used as first guess for the FAST reconstruction



Example reconstruction (Event ID 2): Dotted line = first guess, Solid line = best fit

ID	Event time	TA FD Mono (Prelim.)		FAST (Prelim.)	
		Energy (EeV)	$X_{max}(gcm^{-2})$	Energy (EeV)	$X_{max}(gcm^{-2})$
1	2019/10/25 04:23:52	6.31	793	3.67±0.19	728±27
2*	2020/01/28 08:20:44	3.02	865	1.7±0.3	816±49
3	2020/01/28 11:13:17	1.91	478	1.44±0.1	439±10
4	2022/11/25 09:24:16	1.66	646	1.54±0.13	384±13
5**	2022/11/26 04:42:03	8.13	771	6.6±0.9	509±26
6	2023/02/17 05:13:36	1.55	561	1.29±0.16	533±19
7*	2023/02/20 08:15:51	1.78	867	3.7±0.6	375±30

Example of few reconstructed events, with pre-reconstructed values from TA as first guess

Publications

FAST Collaboration, M. Malacari et al., The First Full-Scale Prototypes of the Fluorescence detector Array of Single-pixel Telescopes, Astropart. Phys. 119 (2020) 102430, [1911.05285]

FAST Collaboration, L. Chytka et al., An automated all-sky atmospheric monitoring camera for a next-generation ultrahigh-energy cosmic-ray observatory, JINST 15 (2020), no. 10 T10009

FAST Collaboration, D. Mandat et al., The prototype opto-mechanical system for the Fluorescence detector Array of Single-pixel Telescopes, JINST 12 (2017), no. 07 T07001

FAST Collaboration, T. Fujii et al., Detection of ultra-high energy cosmic ray showers with a single-pixel fluorescence telescope, Astropart. Phys. 74 (2016) 64–72, [1504.00692]

FAST Collaboration, T. Fujii et al., Recent results from prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST) in both hemispheres, EPJ Web Conf. 283 (2023) 06010

FAST Collaboration, F. Bradfield et al., Reconstruction procedure of the Fluorescence detector Array of Single-pixel Telescopes, PoS ICRC2023 (2023) 303, DOI: https://doi.org/10.22323/1.444.0303

FAST Collaboration, S. Sakurai et al., Detecting ultra-high-energy cosmic rays with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST) in both hemispheres, PoS ICRC2023 (2023) 302, DOI: https://doi.org/10.22323/1.444.0302

FAST Collaboration, T. Fujii et al., Latest results of ultra-high-energy cosmic ray measurements with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST), PoS ICRC2021 (2021) 402, [2107.02949]

J. Albury, Extending the Energy Range of Ultra-High Energy Cosmic Ray Fluorescence Detectors,Ph.D. thesis (2021) University of Adelaide