Osaka Metropolitan University

Fluorescence detector Array of Single-pixel Telescopes

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

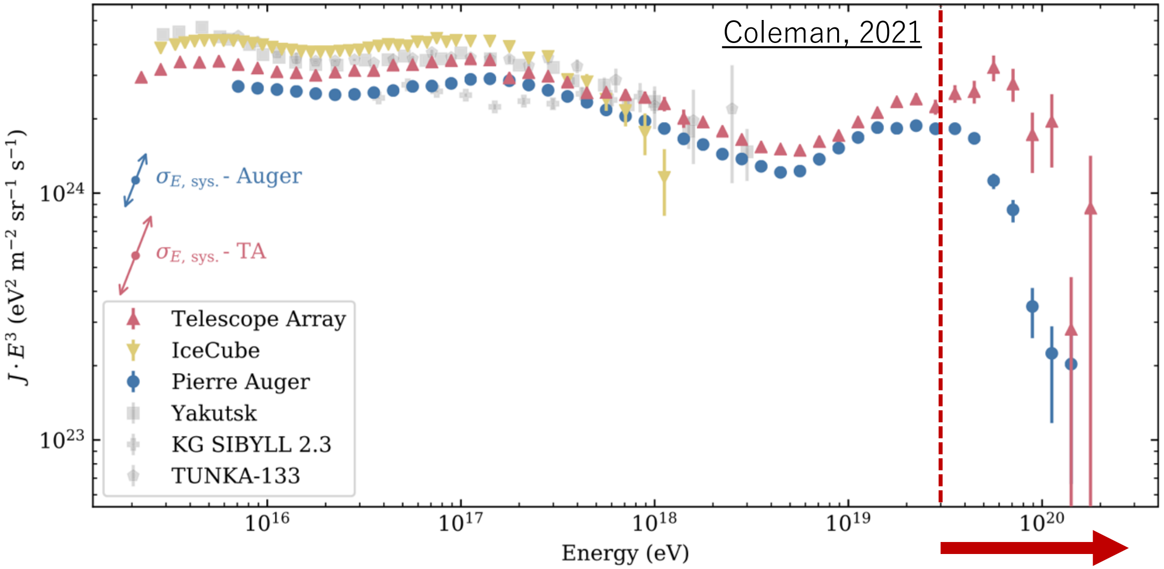
Fraser Bradfield, J. Albury, J. Bellido, L. Chytka, J. Farmer, T. Fujii, P. Hamal, P. Horvath, M. Hrabovsky, V. Jilek, K. Cerny, J. Kmec, J. Kvita, M. Malacari, D. Mandat, M. Mastrodicasa, J. Matthews, S. Michal, H. Nagasawa, H. Namba, M. Niechciol, L. Nozka, M. Palatka, M. Pech, P. Privitera, S. Sakurai, F. Salamida, P. Schovanek, R. Smida, D. Stanik, Z. Svozillikova, A. Taketa, K. Terauchi, S. Tomas, P. Travnicek and M. Vacula (The FAST Collaboration)

UHECR 2024, Malargüe, Pierre Auger Observatory

The Fluorescence Detector Array of Single-pixel Telescopes

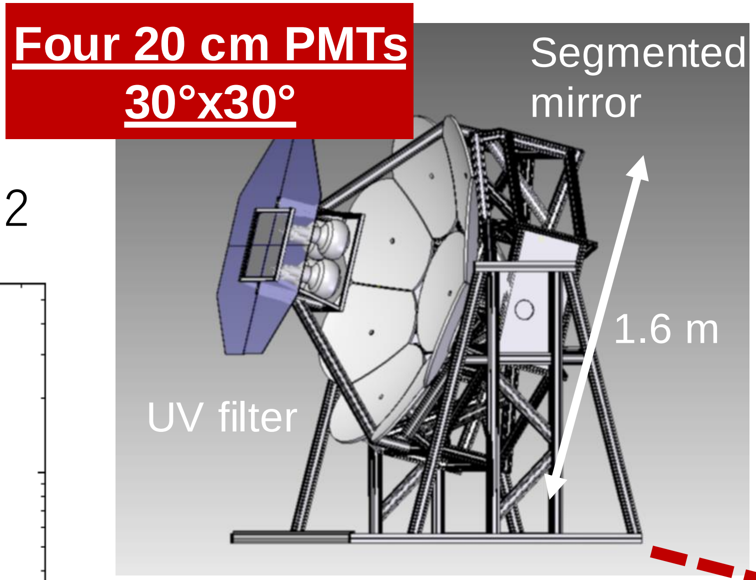
Goal：

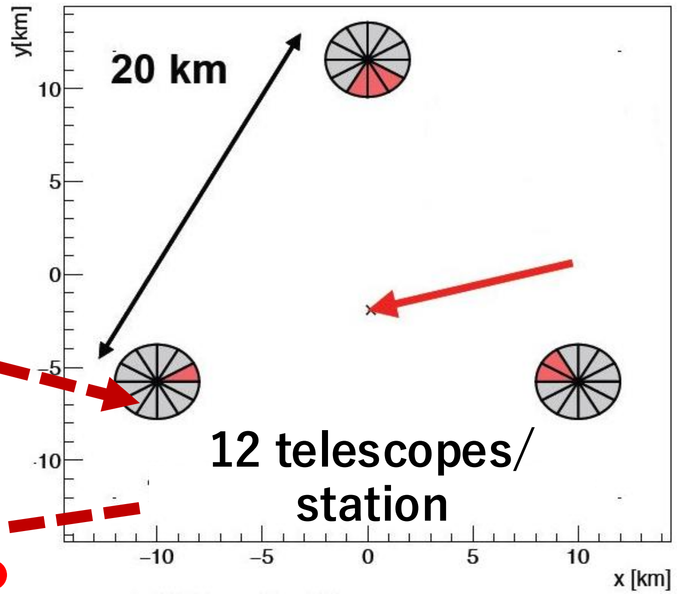
- Uncover origin of UHECRs
- Use same detector in both hemispheres
- Detection area - 150,000 km^2

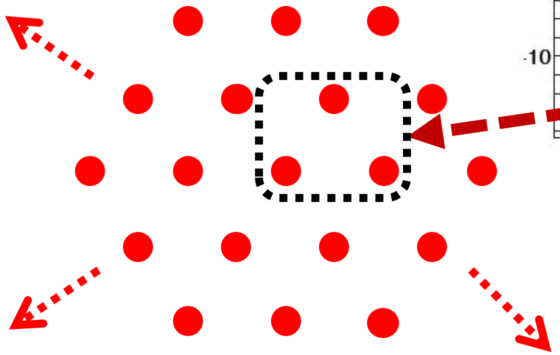


Aiming for 100% trigger efficiency **above $10^{19.5}$ eV**

Design： Low-cost, easily deployable, autonomous fluorescence telescopes







FAST reconstruction

Top-down reconstruction

1）Directly compare data traces to those from simulations

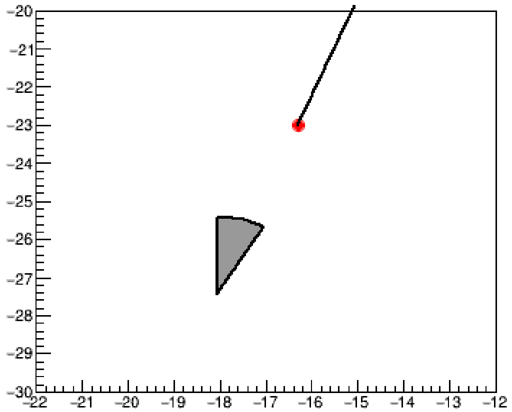
2）The parameters $(E, X_{\mathrm{max}}, \theta, \phi, x, y)$ of the simulation which give the best matching traces to data are chosen

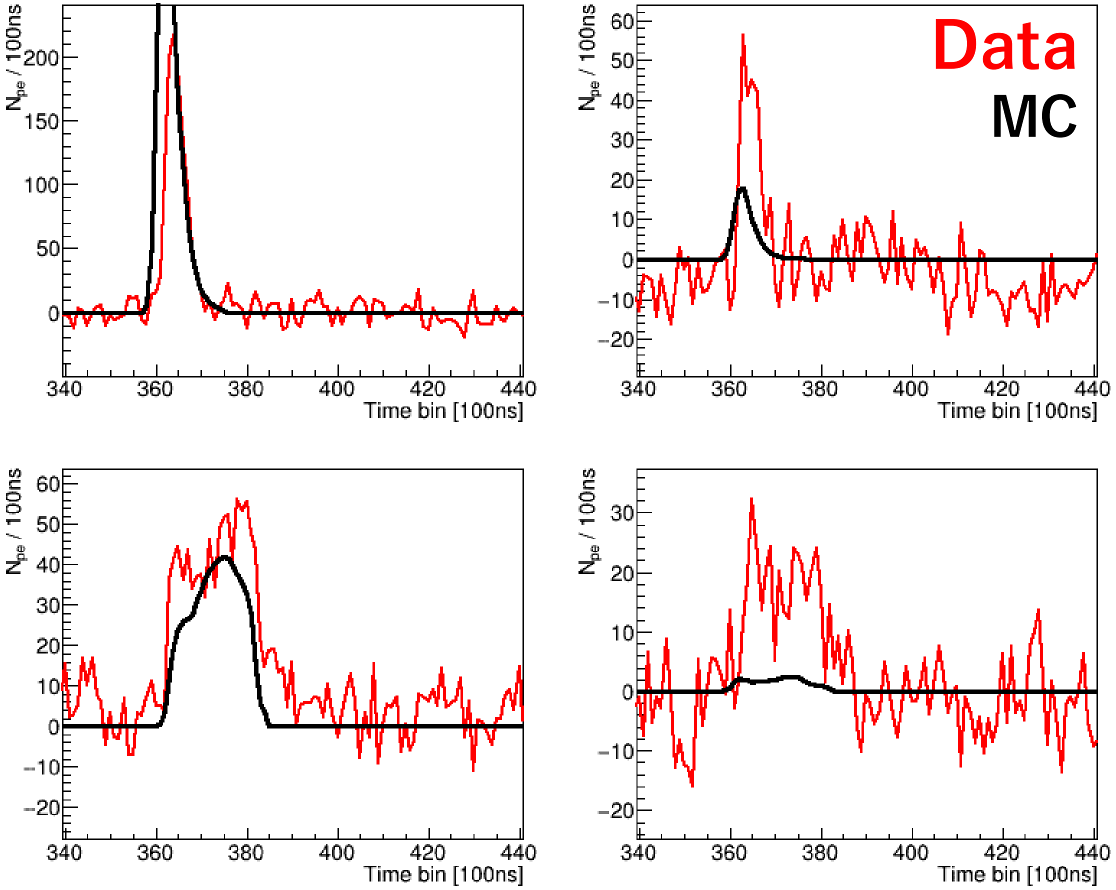
How？Maximize likelihood function

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

Probability of observing signal x_i in time bin i of PMT k given shower parameters $\vec{a} = (E, X_{\mathrm{max}}, \theta, \phi, x, y)$

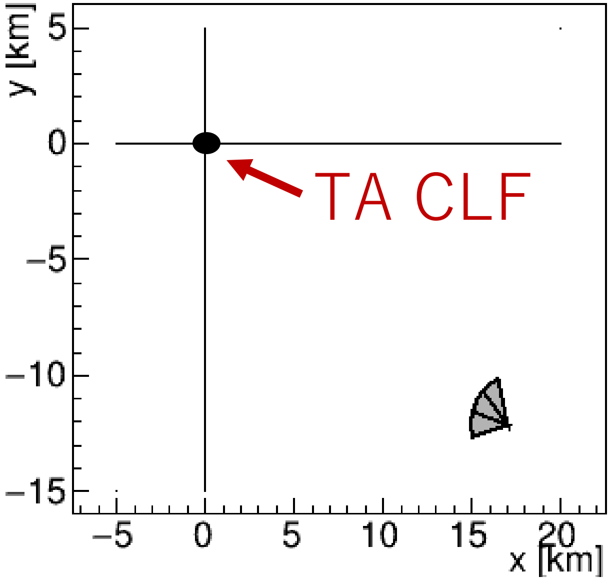
$X_{\mathrm{max}}/(\mathrm{g\ cm^{-2}})$ = 746.06
Energy/EeV = 0.88
Zenith/° = 55.85
Azimuth/° = 68.41
CoreX/m = -16298
CoreY/m = -22993
Likelihood = 21198.9





First generation prototypes

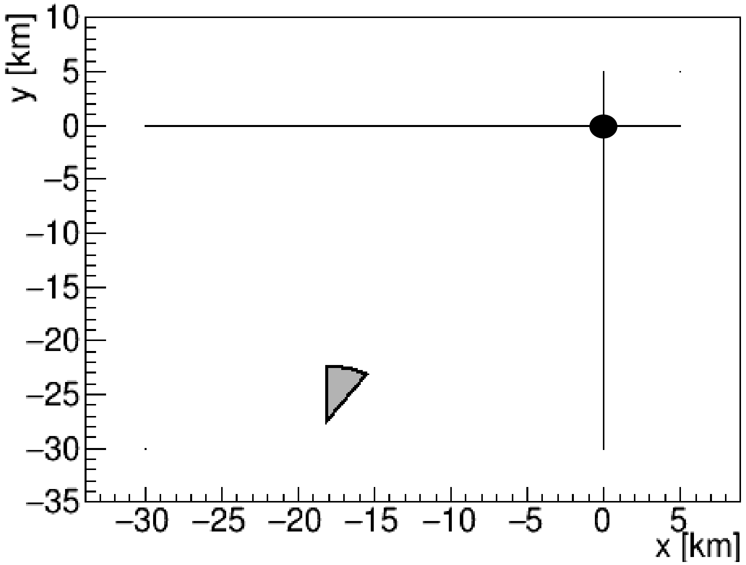
"FAST@TA"



Observation time:
~540 hrs

"FAST@Auger"

Only one in operation



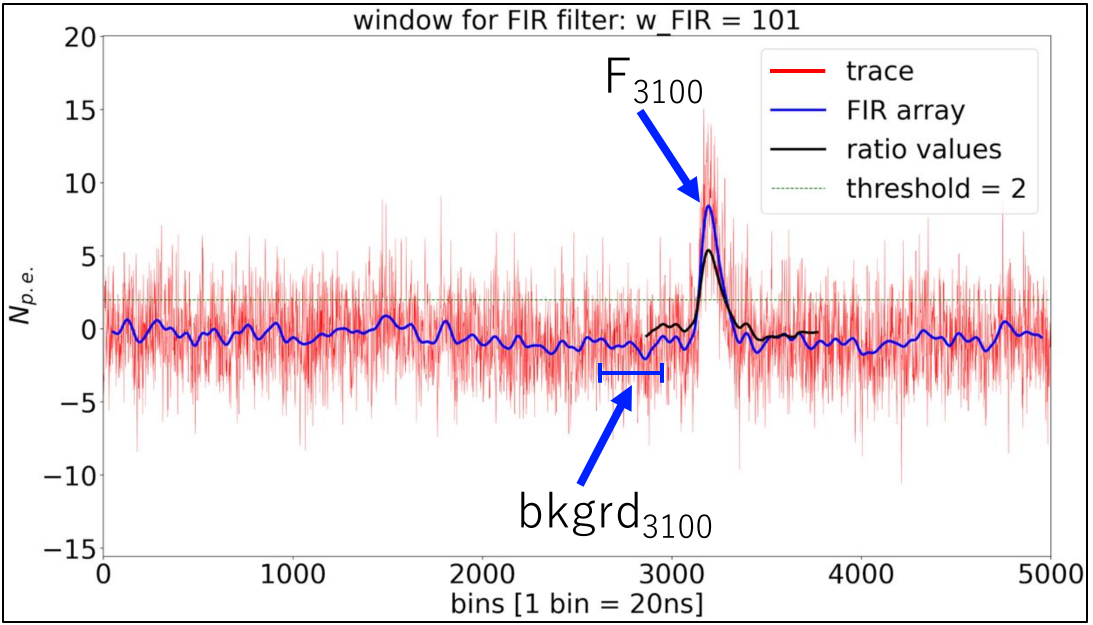
Observation time:
~2970 hrs

Thanks to dedicated shift team!

Coincidence events

	FAST@TA	FAST@Auger
Analysis period	2 telescopes (2018/03 – 2018/10) 3 telescopes (2018/10 – 2023/02)	1 telescope (2022/07 – 2022/10)
Observation time	2 telescopes ~ 65 hrs 3 telescopes ~ 182 hrs	1 telescope ~ 122 hrs
Trigger condition	External trigger from TA BRM FD	External trigger from Auger LL Bay 4
Coincidence events	**438**	**236**

Signal detection algorithm:



For event observed by TA/Auger in FOV of FAST:

- Smooth original trace 'T' with a finite impulse response (FIR) filter → get waveform 'F'
- For the ith bin of F, F_i, calculate

$$\mathrm{SNR} = \frac{F_i - \mu(\mathrm{bkgrd}_i)}{\sigma(\mathrm{bkgrd}_i)} \quad \mathrm{bkgrd}_i = (F_{i-500}, F_{i-200})$$

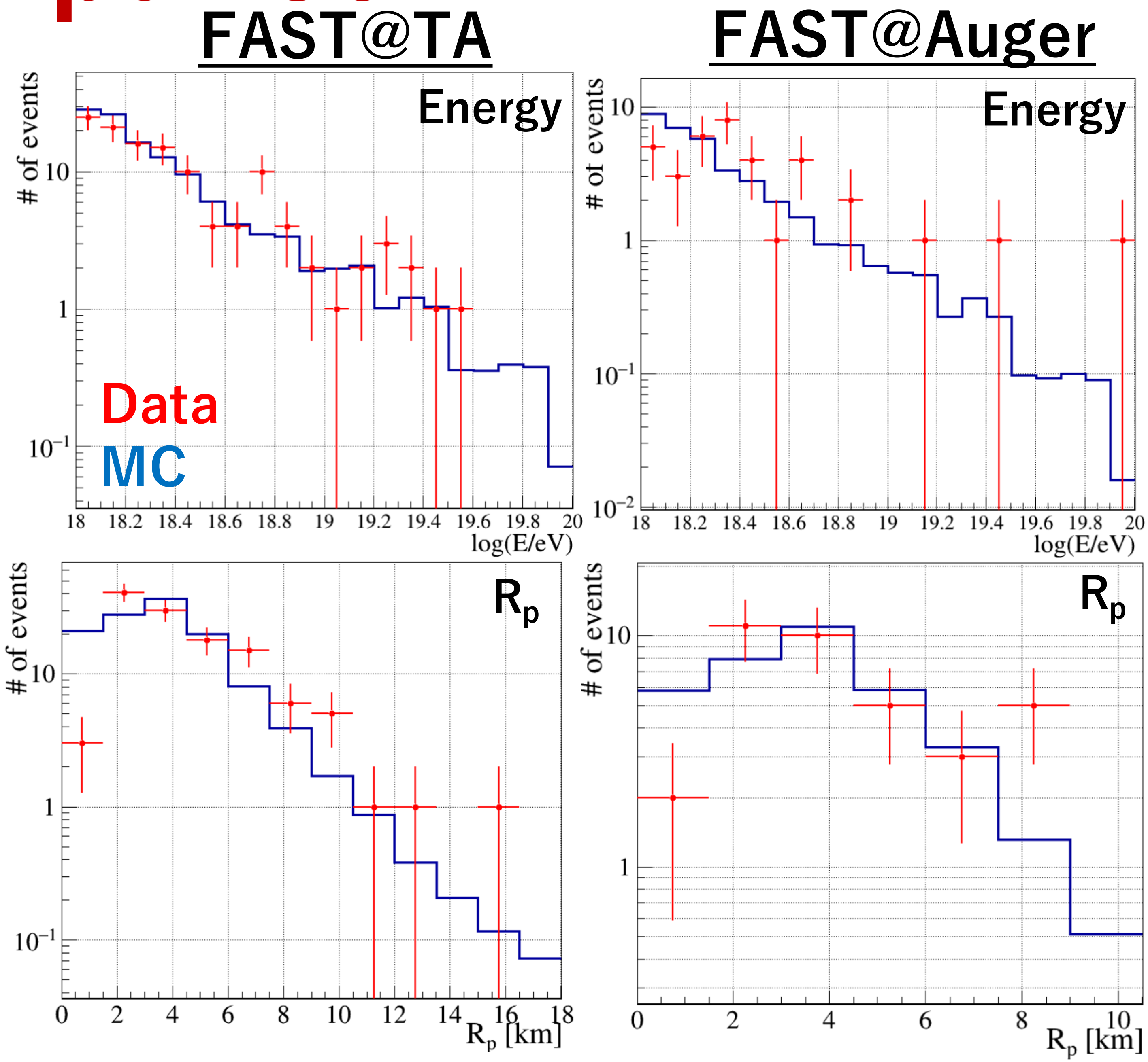
PMT has signal if the max SNR over all bins > 2

Data/MC comparison

- **Data** = TA/Auger reconstructed values ($E > 10^{18}$ eV)

- **MC Conditions**
  - X_{max} dist. : EPOS (500-1200 gcm^{-2})
  - Energy dist. : E^{-1} (10^{18}-10^{20} eV)
  - θ dist. : $\sin\theta\cos\theta$ (0-80 deg)
  - FAST@TA
    - Core pos : Circle at (0,0) r = 35 km
  - FAST@Auger
    - Core pos : Circle at (0,0) r = 12 km
  - Trigger cond. : 2 PMTs with SNR>6

- MC histograms rescaled to match area of data histograms



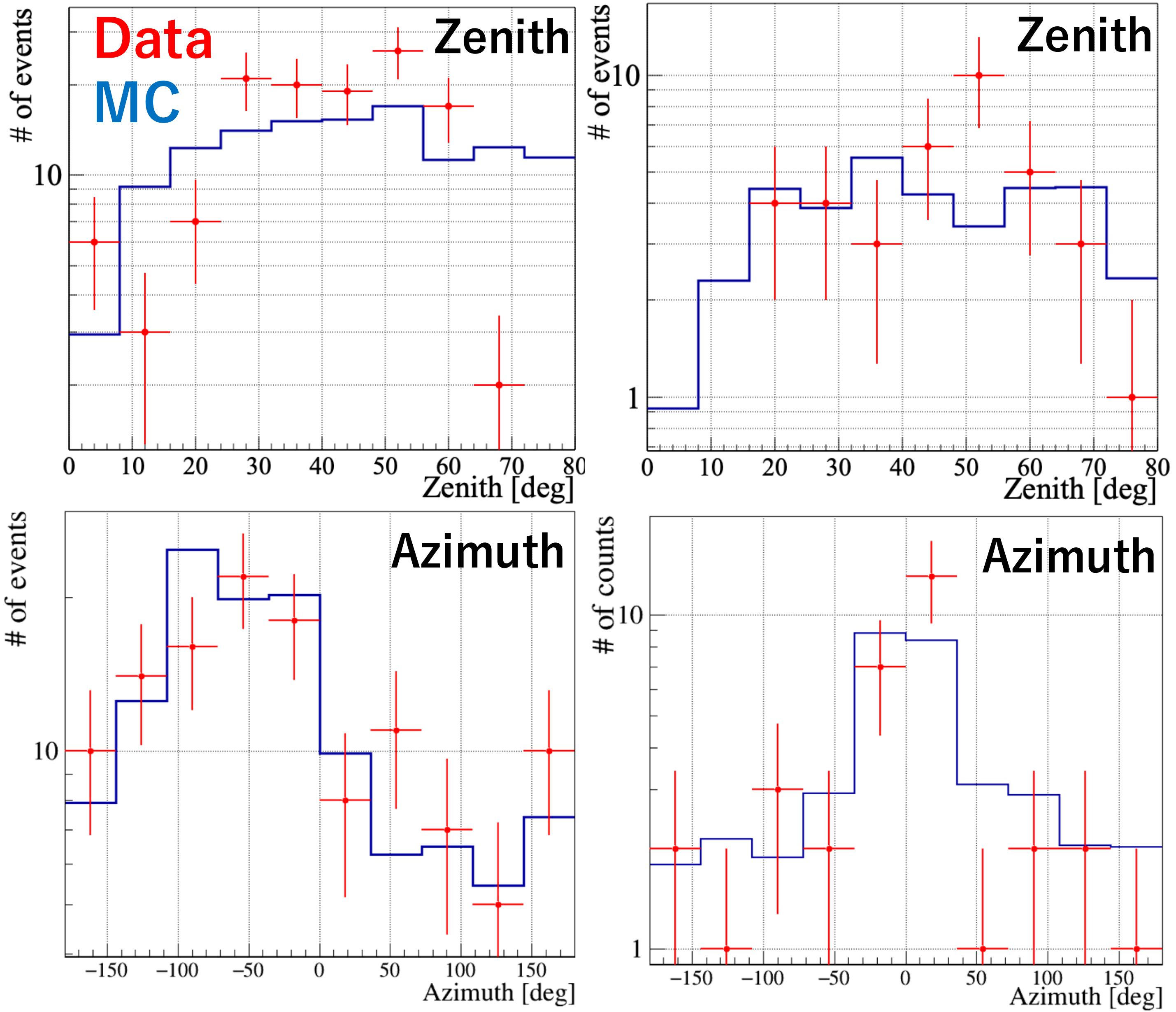
Data/MC comparison

- **Data** = TA/Auger reconstructed values ($E > 10^{18}$ eV)

- **MC Conditions**
  - X_{max} dist.：EPOS (500-1200 gcm^{-2})
  - Energy dist.： E^{-1} (10^{18}-10^{20} eV)
  - θ dist.： $\sin\theta\cos\theta$ (0-80 deg)
  - FAST@TA
    - Core pos：Circle at (0,0) r = 35 km
  - FAST@Auger
    - Core pos： Circle at (0,0) r = 12 km
  - Trigger cond.：2 PMTs with SNR>6

- MC histograms rescaled to match area of data histograms

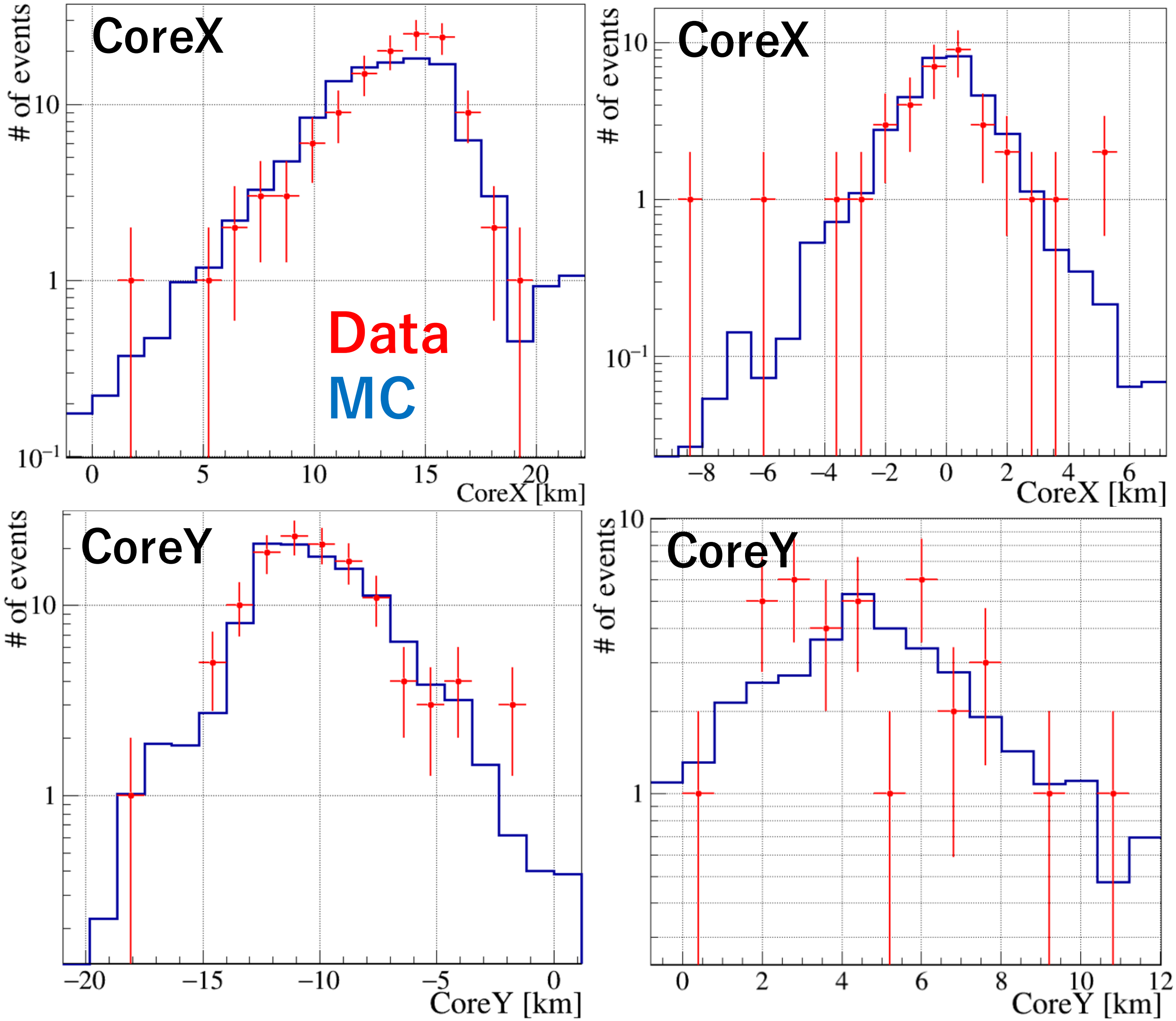
FAST@TA **FAST@Auger**



Data/MC comparison

- **Data** = TA/Auger reconstructed values ($E > 10^{18}$ eV)
- **MC Conditions**
  - X_{max} dist.：EPOS (500-1200 gcm^{-2})
  - Energy dist.： E^{-1} (10^{18}-10^{20} eV)
  - θ dist.： $\sin\theta\cos\theta$ (0-80 deg)
  - FAST@TA
    - Core pos：Circle at (0,0) r = 35 km
  - FAST@Auger
    - Core pos： Circle at (0,0) r = 12 km
  - Trigger cond.：2 PMTs with SNR>6
- MC histograms rescaled to match area of data histograms

FAST@TA **FAST@Auger**

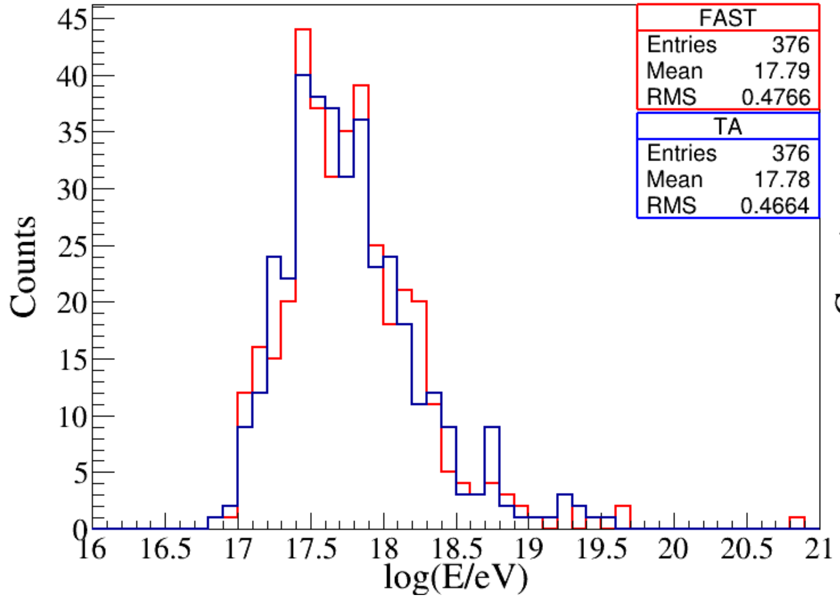


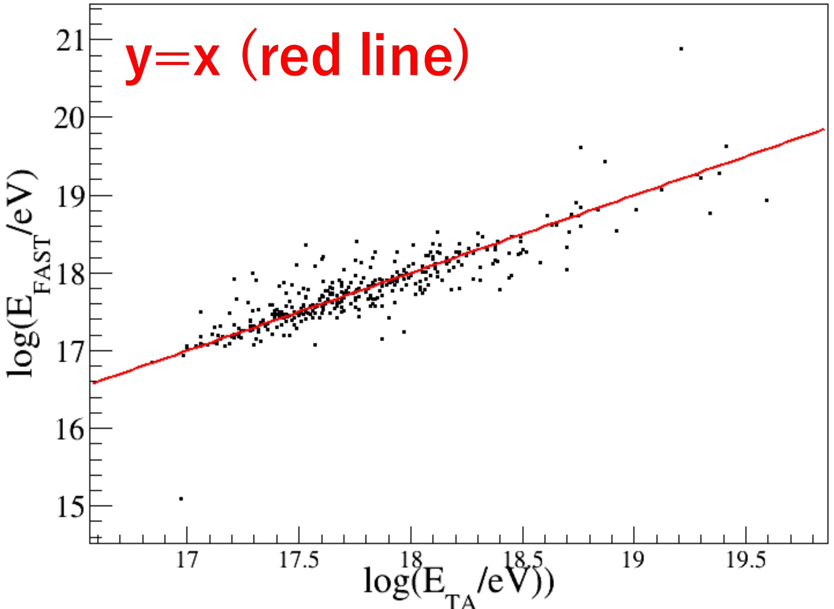
Reconstruction results

Reconstruction setup

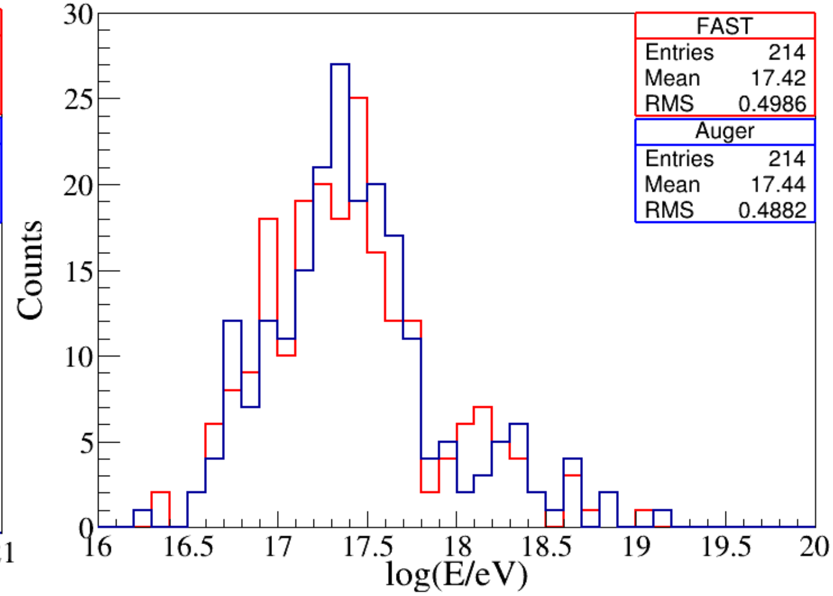
- Recon. (E, X_{max}, θ, ϕ, x, y) + fit time offset
- Use the TA/Auger reconstructed values as first guess
- Cuts：
  - Successful minimization of likelihood
  - Best fit time offset between (100,500)

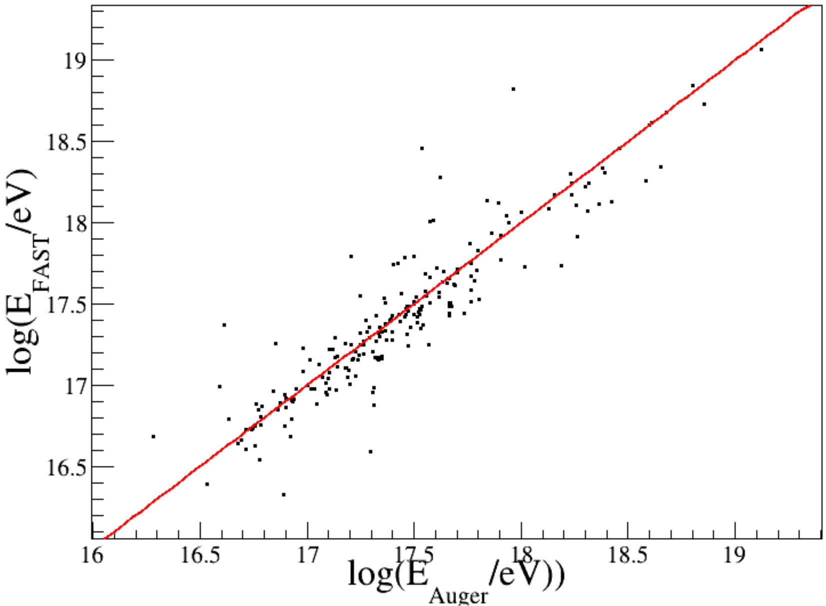
FAST@TA





FAST@Auger



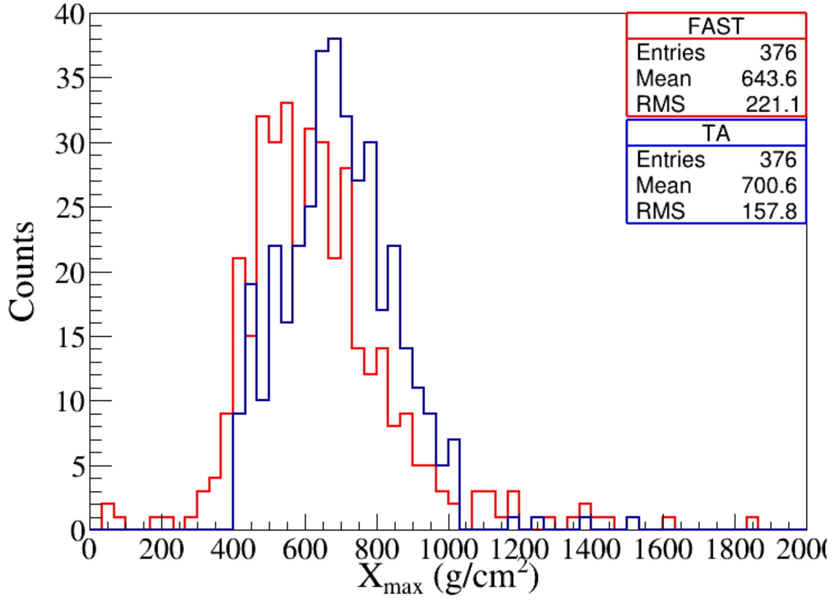


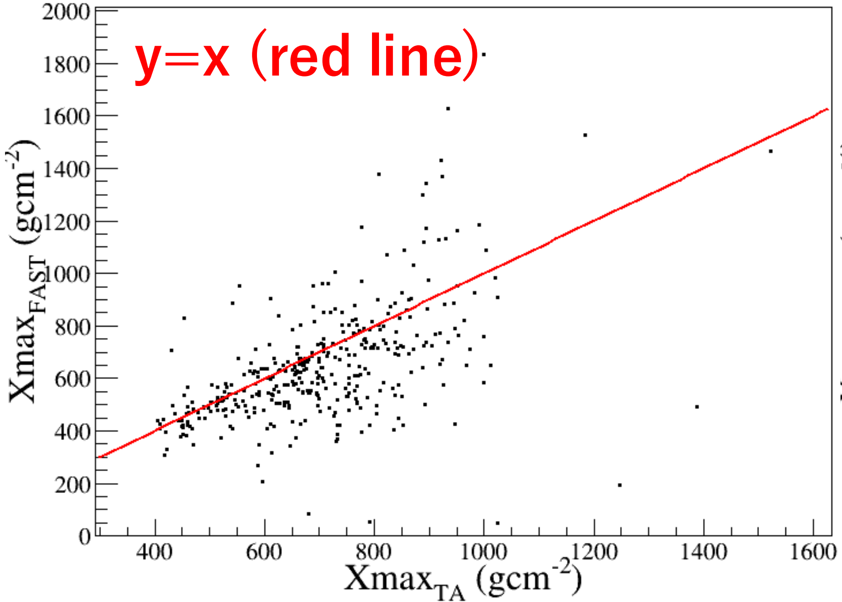
Reconstruction results

Reconstruction setup

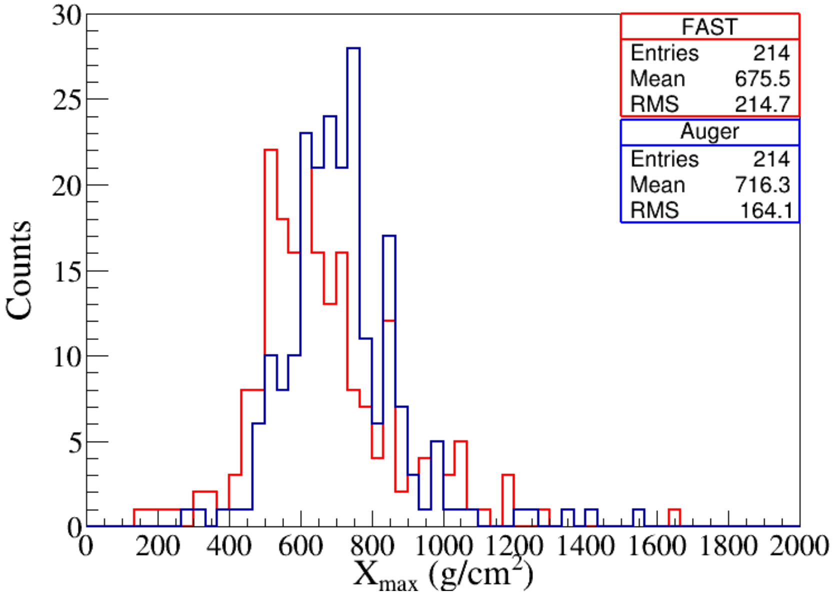
- Recon. (E, X_{max}, θ, ϕ, x, y) + fit time offset
- Use the TA/Auger reconstructed values as first guess
- Cuts：
  - Successful minimization of likelihood
  - Best fit time offset between (100,500)

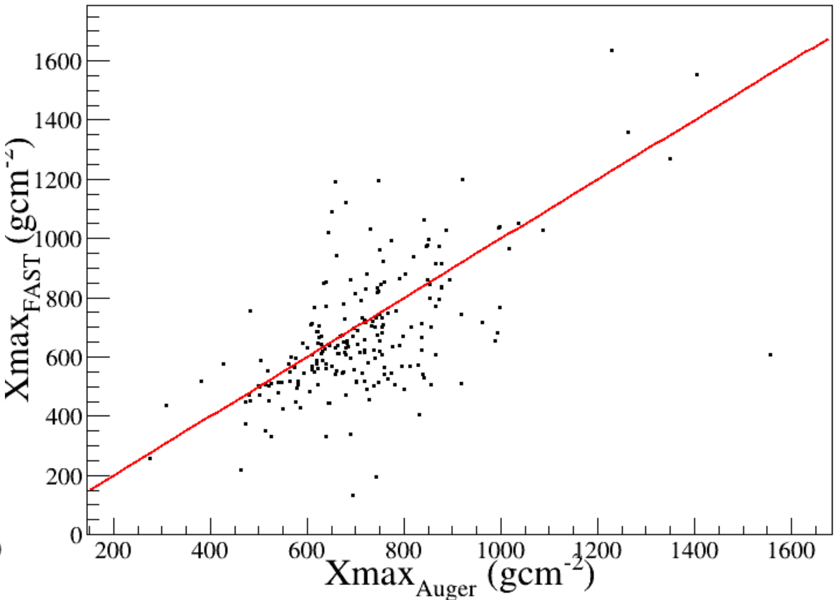
FAST@TA





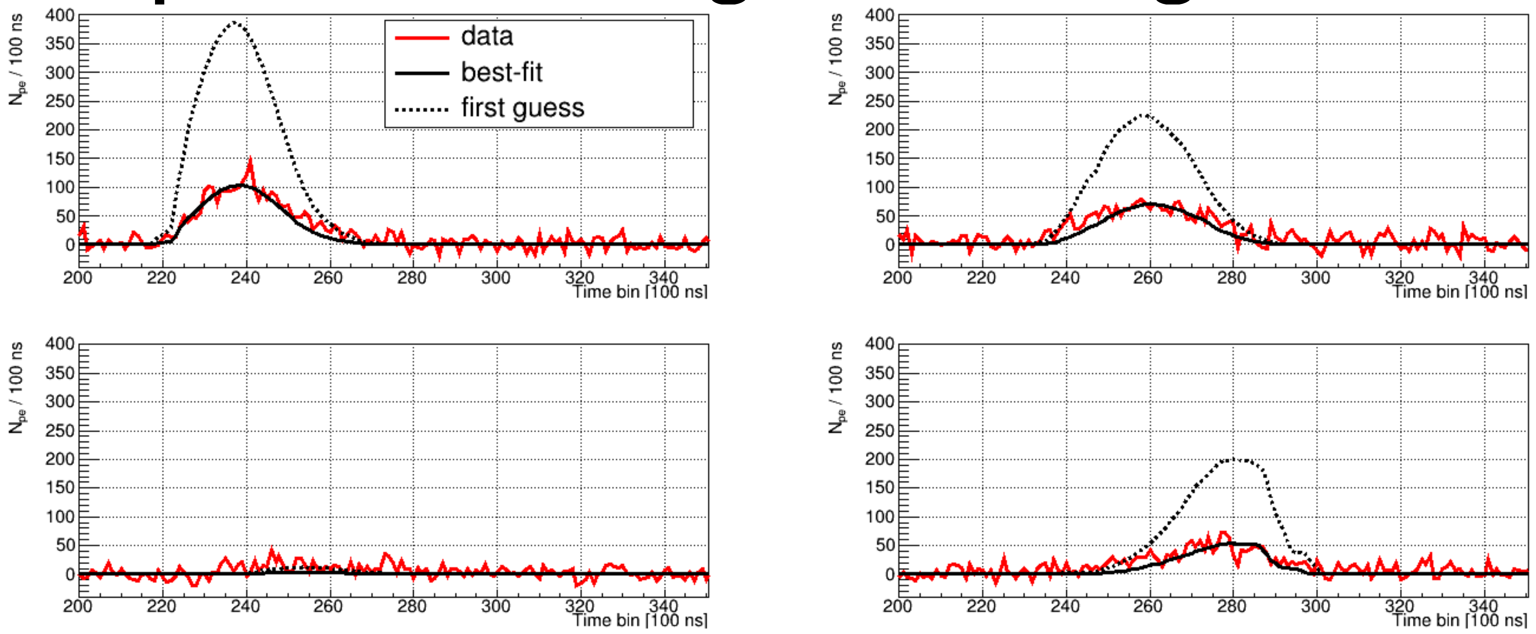
FAST@Auger

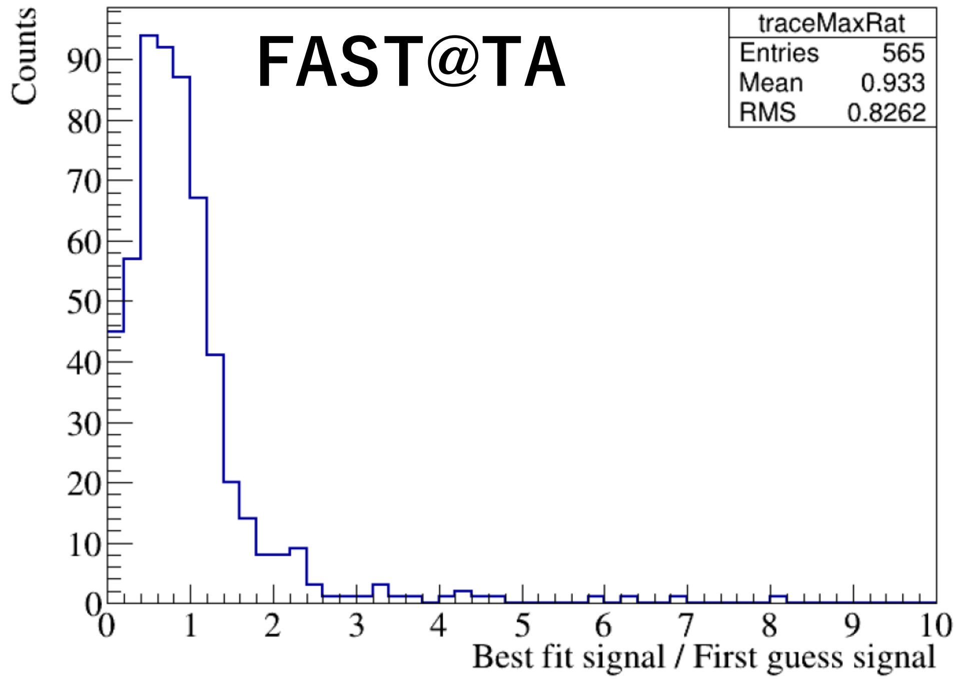


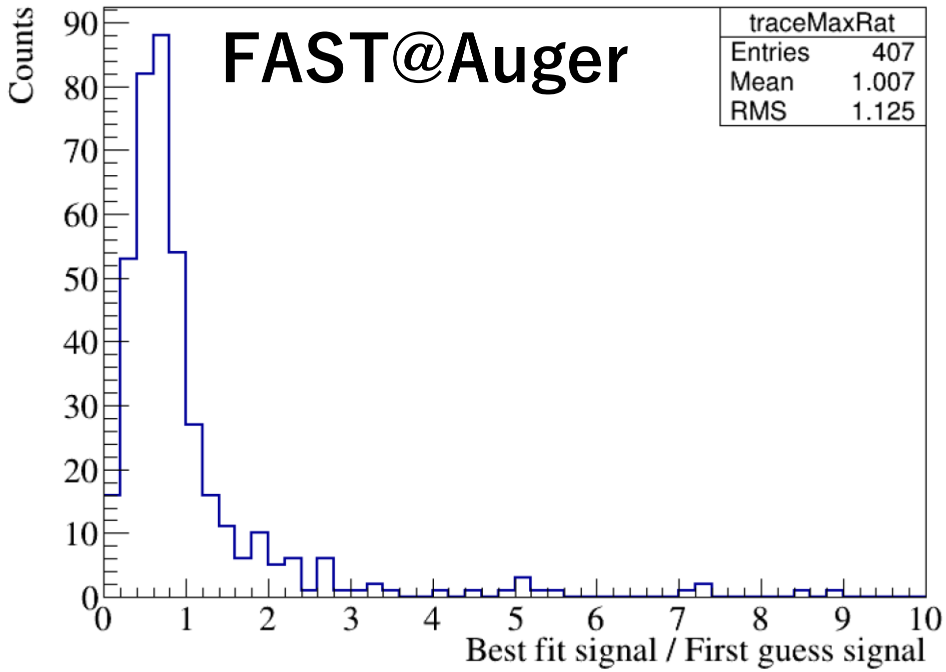


Source of X_{max} bias

- On average, signal in data is lower than expected from Auger/TA first guess







Possible reasons for difference

Filter efficiency degradation

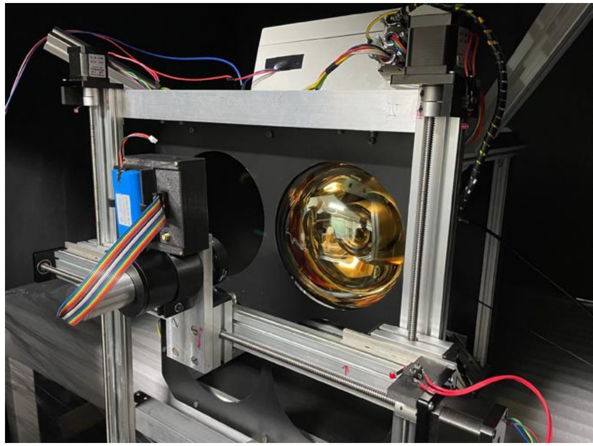
Atmospheric changes

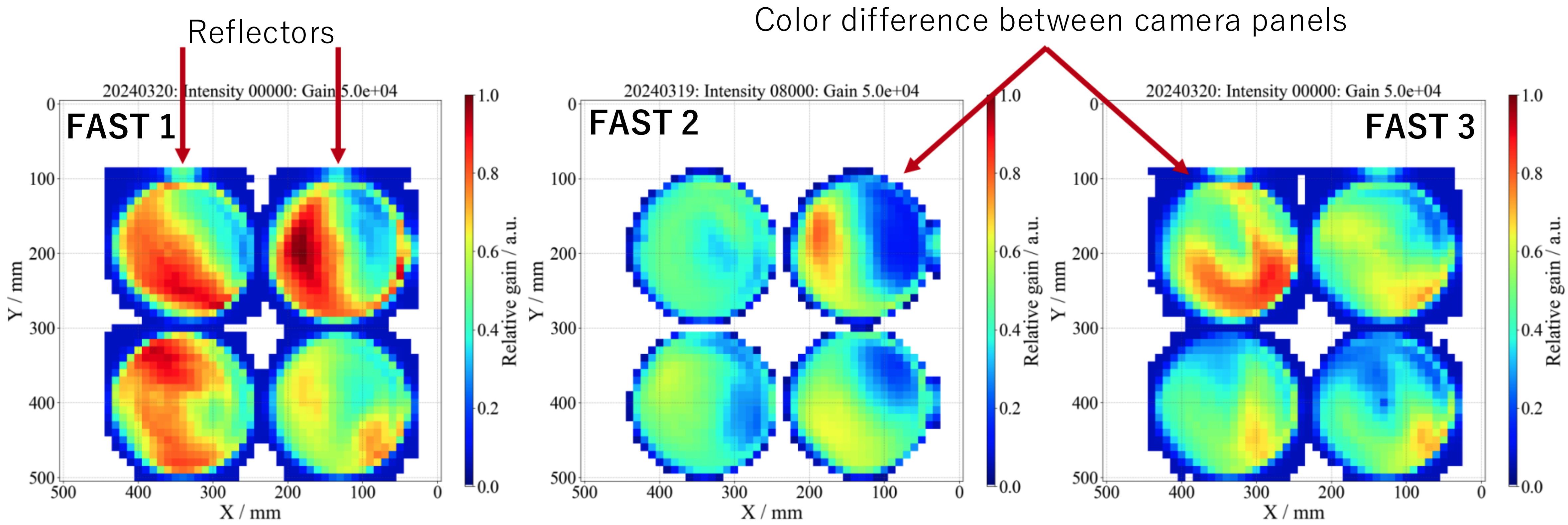
Baseline fluctuations

PMT response (deterioration/structure)

FAST@TA PMT uniformity measurements

To check telescope performance, measured response of FAST@TA PMTs on site Mar. 2024 using PMT scanner

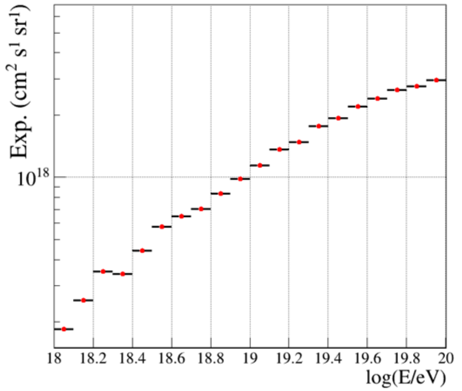




~60% (std-dev) non-uniformity was observed.
This is not accounted for in simulations...

Energy spectrum

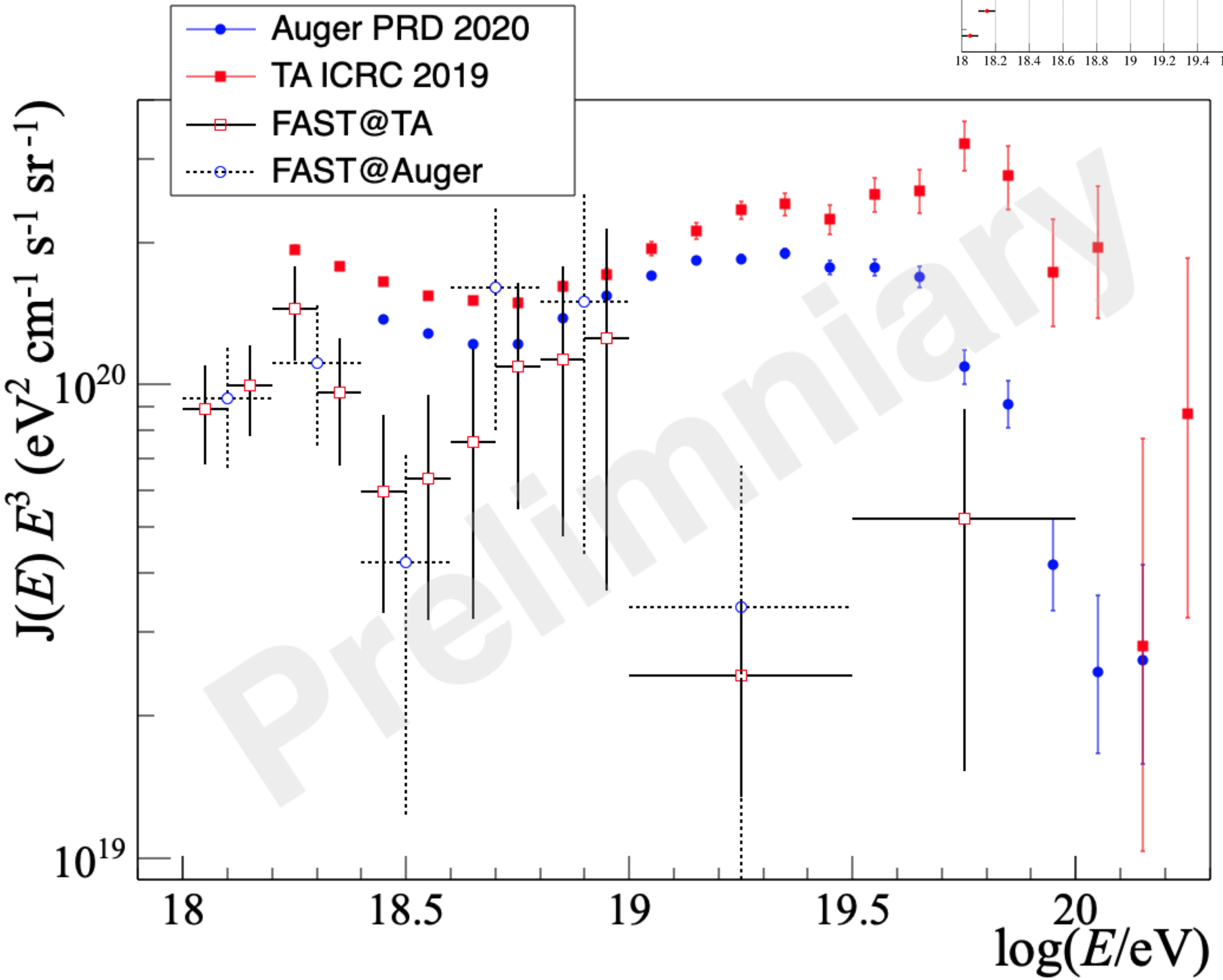
E.g. FAST@Auger exposure (~122 hrs)



First energy spectrum from FAST

- Calculated from the reconstructed energy values and exposure determined with simulations used for data/MC comparison

- The FAST@TA and FAST@Auger results agree within statistical uncertainty

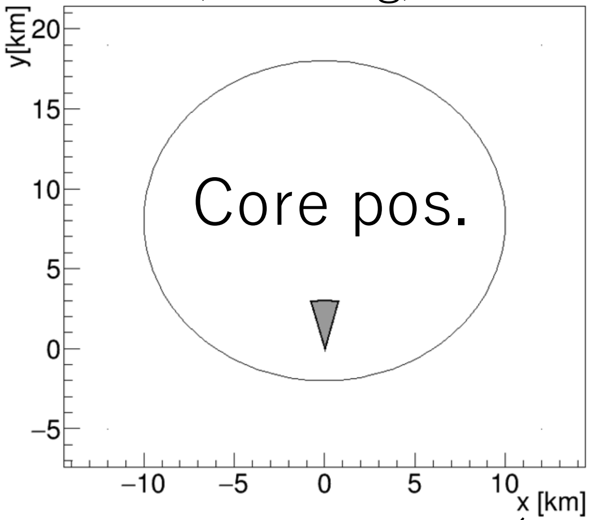


Elongation rate – Comparison with EPOS

Construct X_{max} rails for FAST

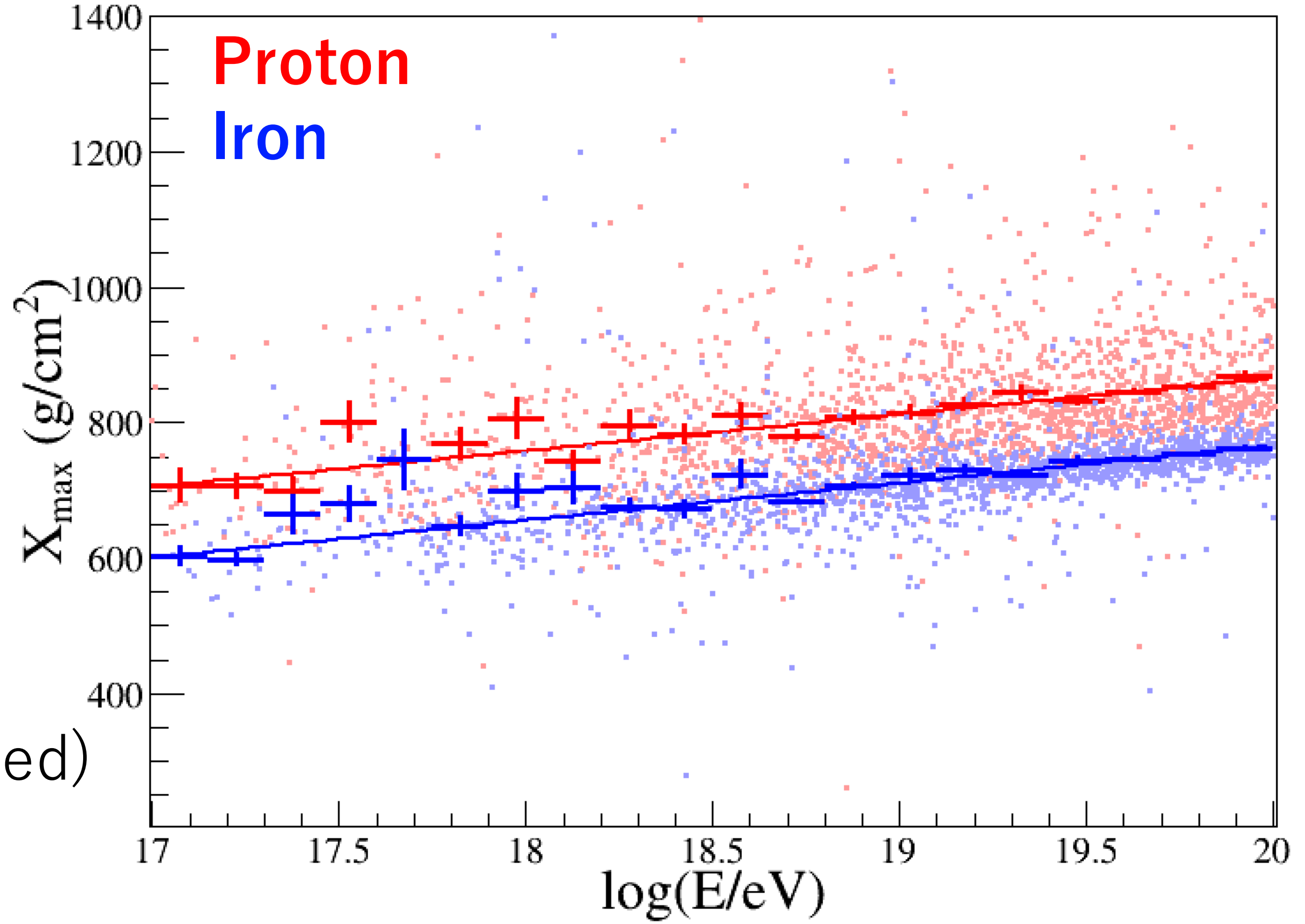
Simulation conditions:

- X_{max} dist. : EPOS (500-1200 gcm^{-2})
- Energy dist. : E^{-1} (10^{18}-10^{20} eV)
- θ dist. : $\sin\theta\cos\theta$ (0-80 deg)



Reconstruct only X_{max} & E (geometry fixed)

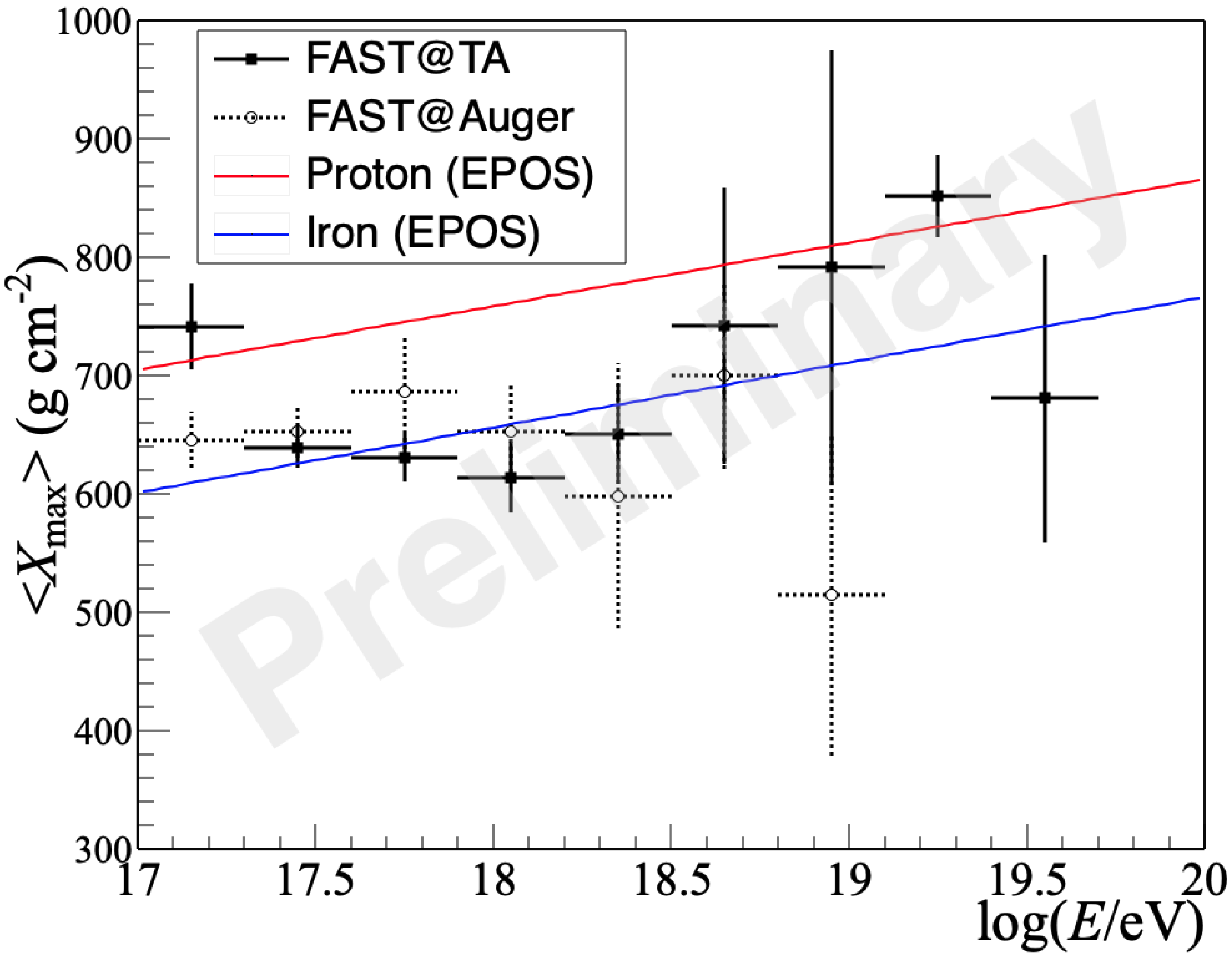
- Initial X_{max} and E varied by 30g/cm2 and 10%
- Cuts:
  - One PMT with SNR>6
  - Successful minimization
  - Relative uncertainty in E & X_{max} both < 0.5



Fitting proton & iron showers separately between 17 < log(E/eV) < 20

Elongation rate

- Proton and iron rails estimated from FAST MC
- Around $10^{17.5}$-$10^{18.5}$ eV the composition estimated by FAST tends toward iron
- FAST@TA and FAST@Auger results agree within statistical uncertainty



Second generation prototypes

Designed to operate "in-the-field" without connection to Auger/TA

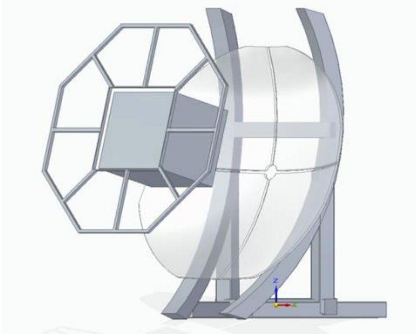
- "FAST-Field telescope"
- Comms. with telescopes at LL via 5 GHz Wifi

Improvements:

- Mirrors (simplified production, 9→4 segments)
- Enclosure (smaller, self sufficient power system)
- Camera (new electronics and PMTs)

Testing at Ondrejov

- FOV measured ✓
- Solar power test ✓
- Pedestal ✓
- Amplifier ✓



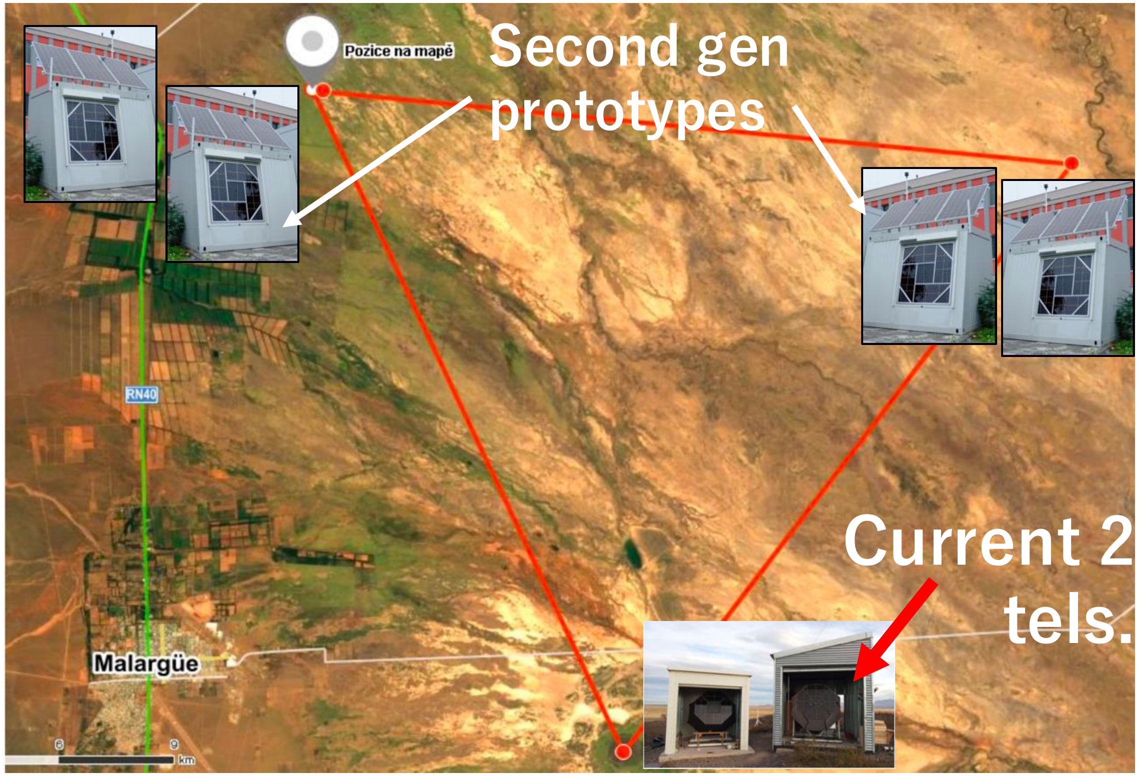
FAST mini-array

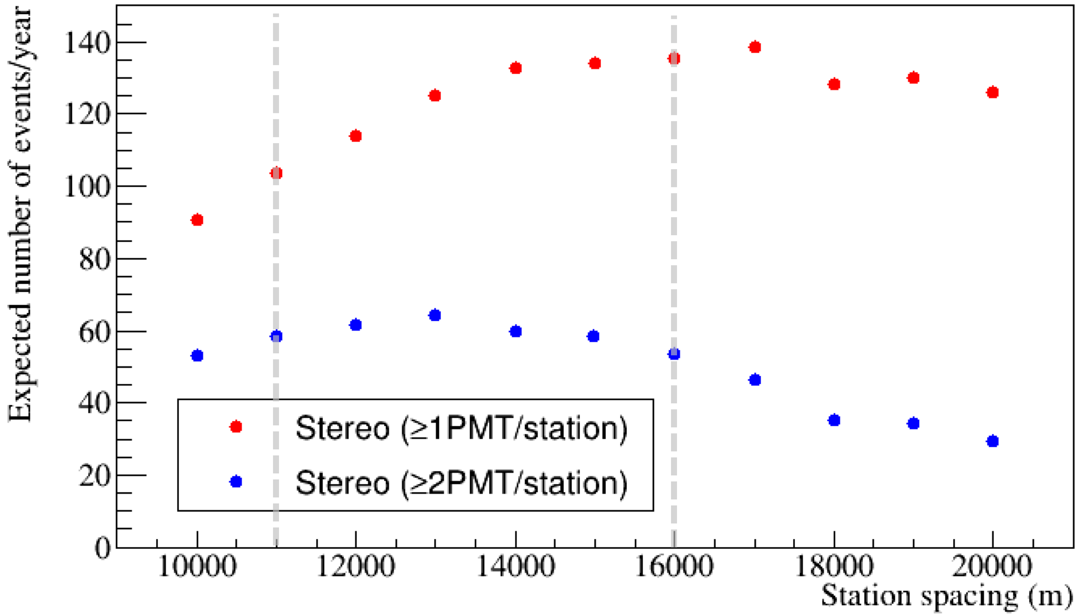
Stereo observation with FAST:
- Install 4 second gen. telescopes at Auger to form triangle with current prototypes

Spacing estimation:

- Estimated # of events FAST mini-array will detect in one year as function of station spacing

- Start with **~11km** spacing (validate stereo observation with high quality events) then move to **~16km** to increase statistics





FAST mini-array

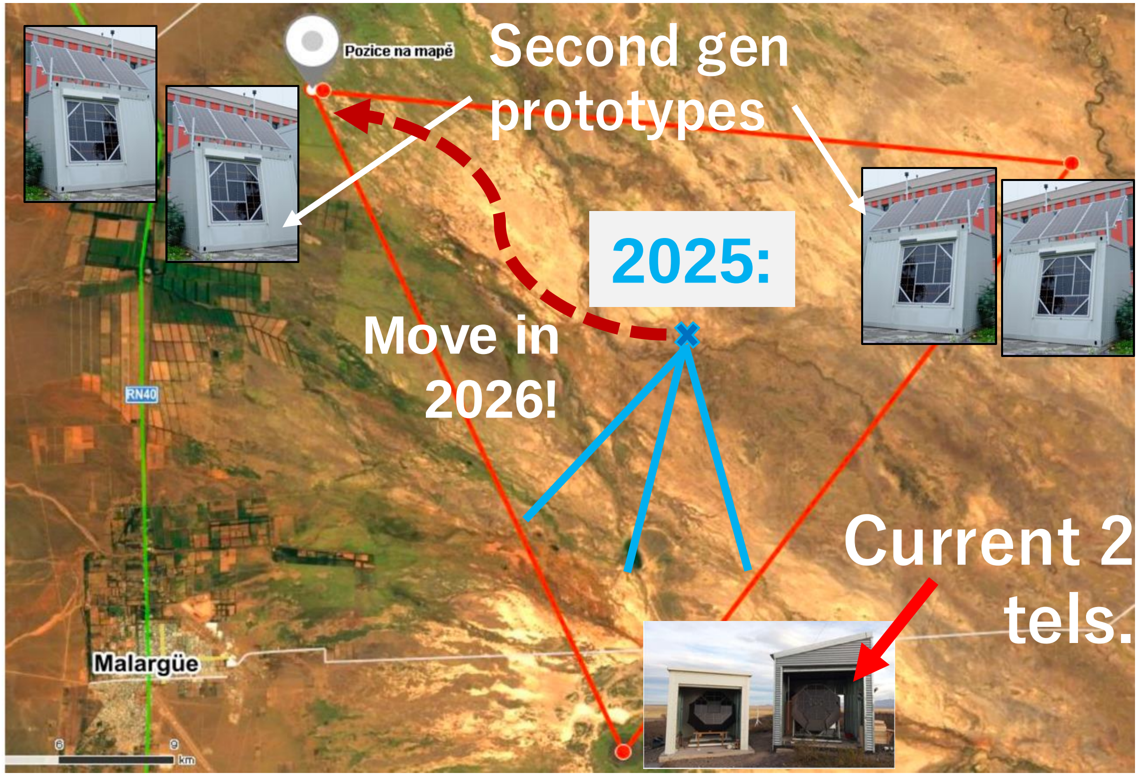
Stereo observation with FAST:

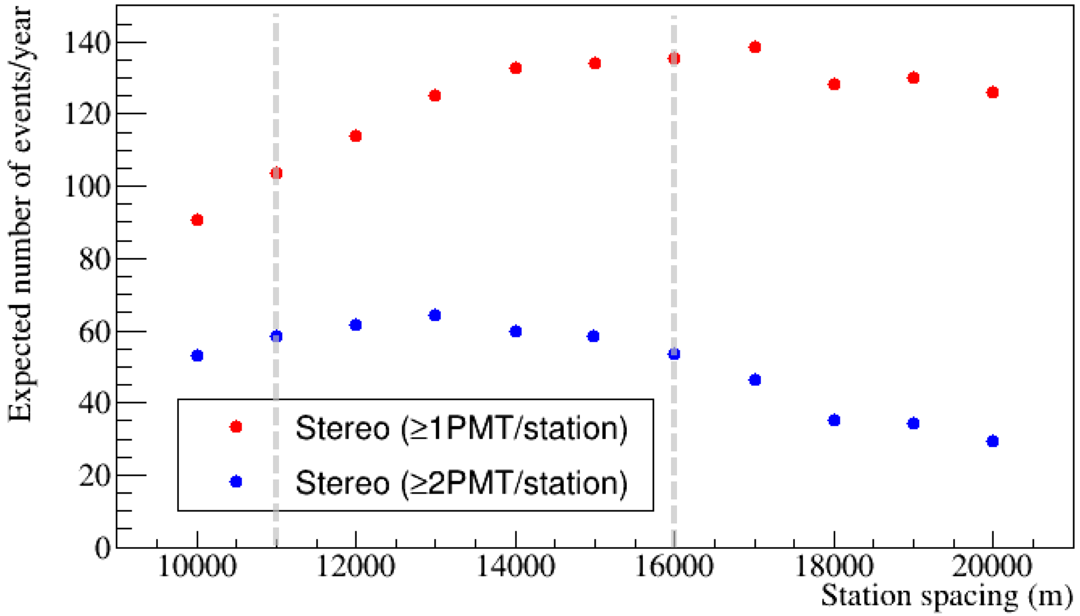
- Install 4 second gen. telescopes at Auger to form triangle with current prototypes

Spacing estimation:

- Estimated # of events FAST mini-array will detect in one year as function of station spacing

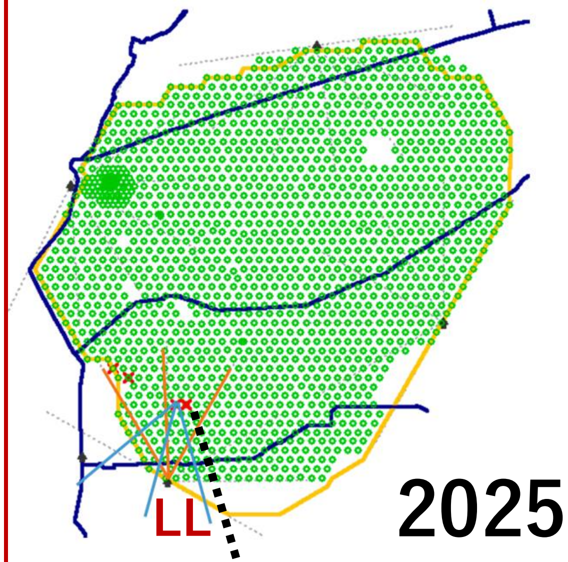
- Start with **~11km** spacing (validate stereo observation with high quality events) then move to **~16km** to increase statistics



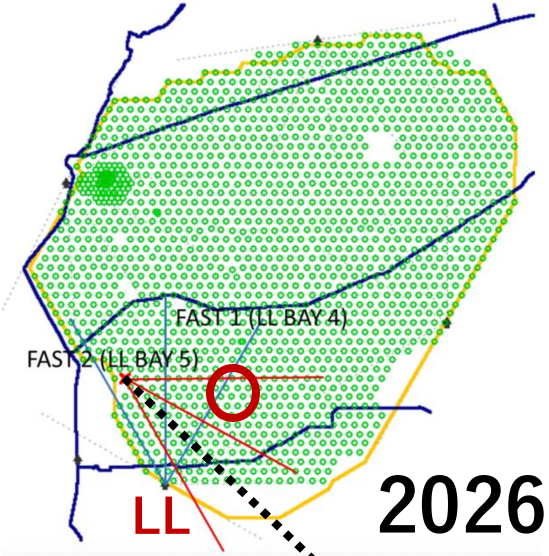


FAST mini-array – site inspection

Soil inspection ✓



Soil inspection ✓



Soil composition:
Solid, earthy soil (no stones)

Can use ground screws for installation

Summary & future

Fluorescence detector Array of Single-pixel Telescopes

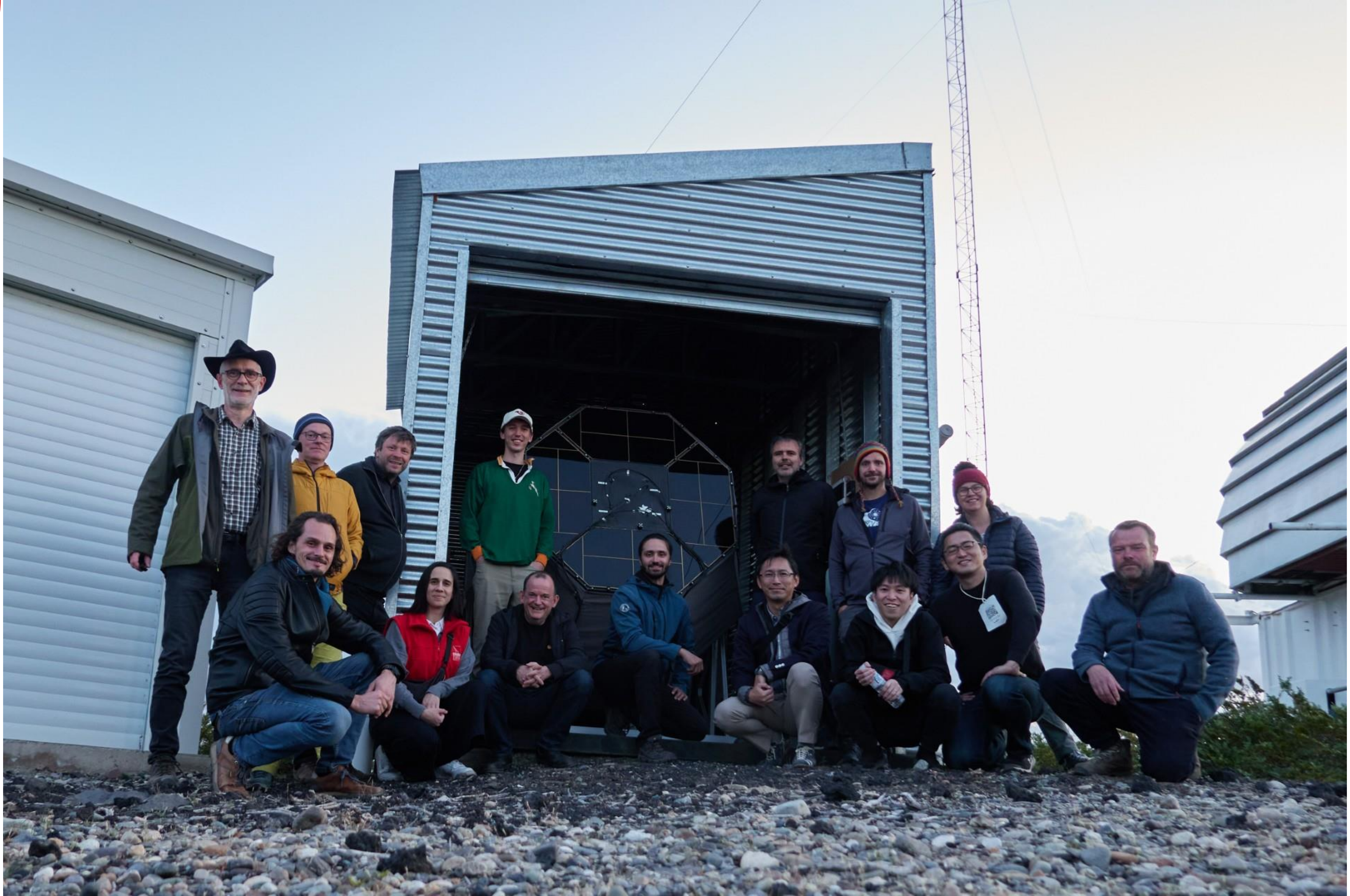
- **FAST** - low cost, easily deployable, autonomous fluorescence telescopes for detecting UHECRs

- Over 650 coincidences between FAST and Auger/TA
  - Simulations seem to reproduce data
  - Estimated the **elongation rate** and **energy spectrum** using ~600 events

- **FAST mini-array** will test second gen prototypes with stereo observation
  - Site inspection complete. Initial station spacing **~11km**

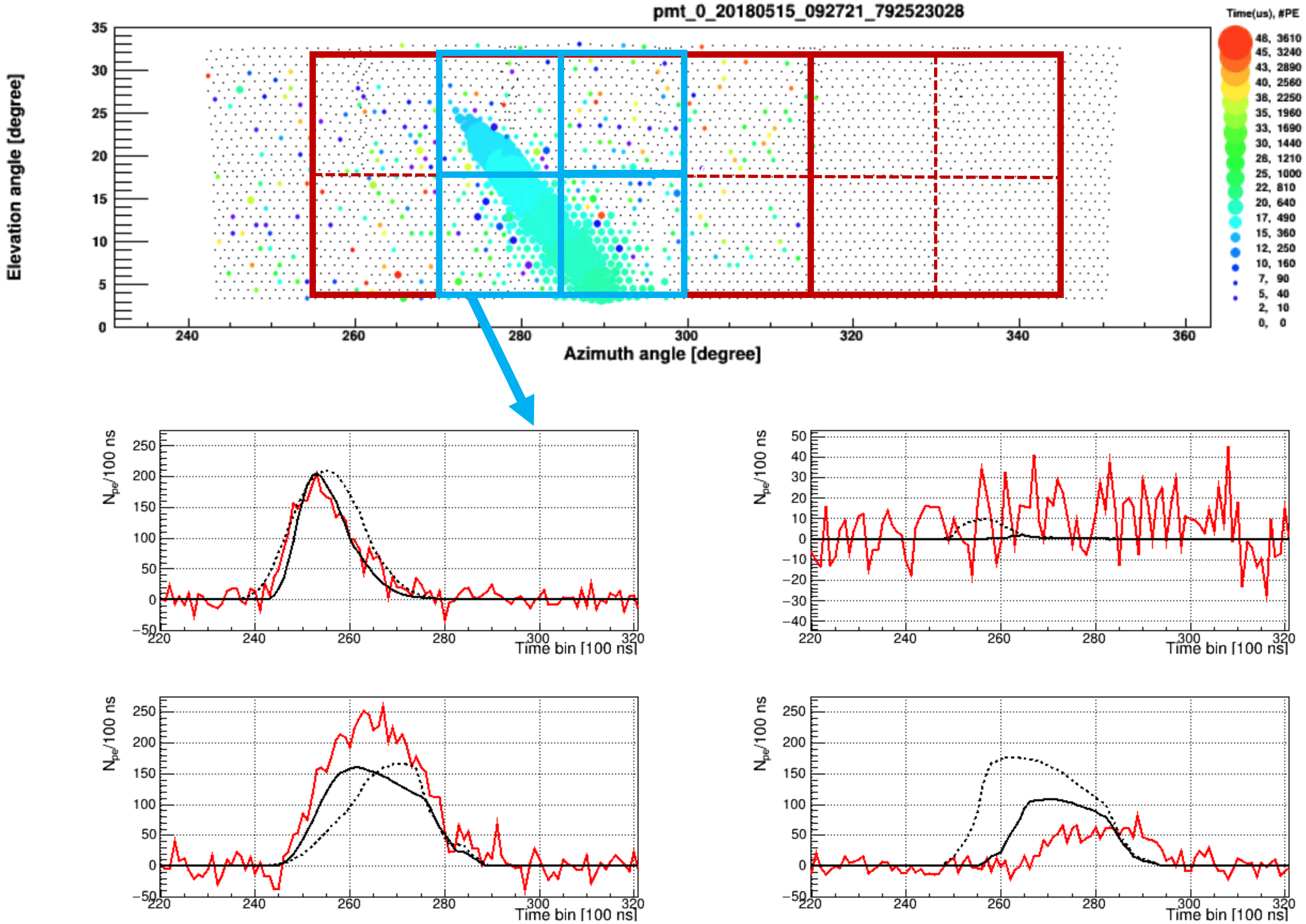
- Include PMT non-uniformity measurements etc. in simulation (check FAST@Auger PMTs)

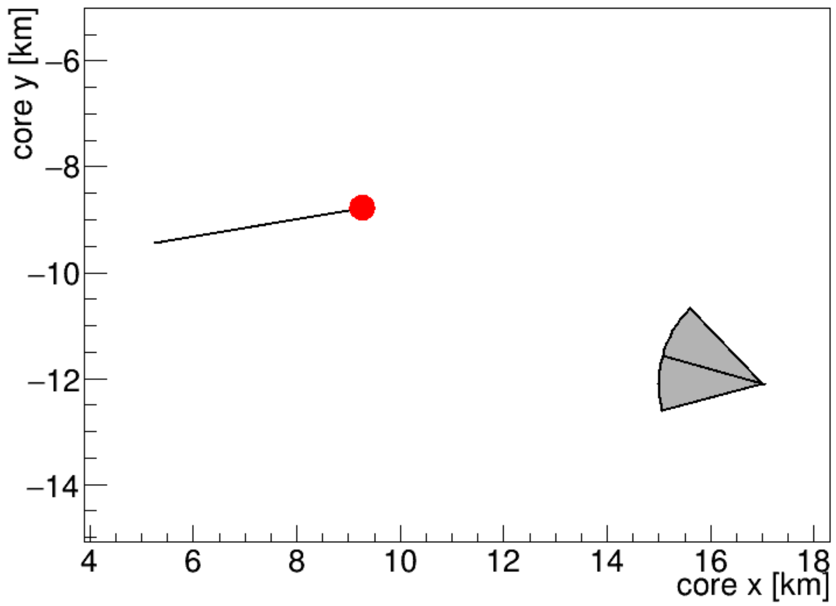
- Finish testing in Ondrejov, ship telescopes to Auger, install, test → **stereo observation early 2025**



Backup

Example events - TA event 1

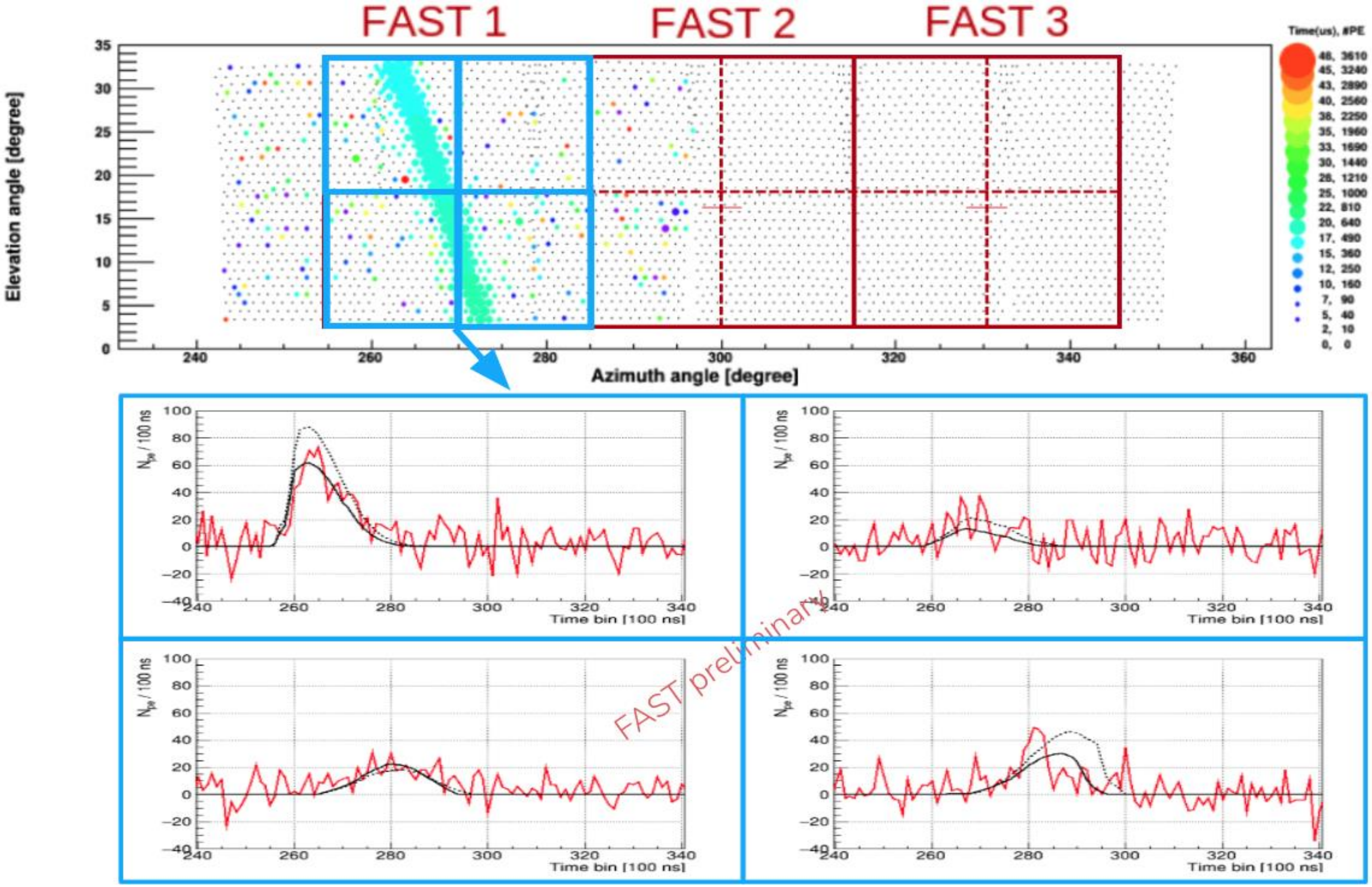


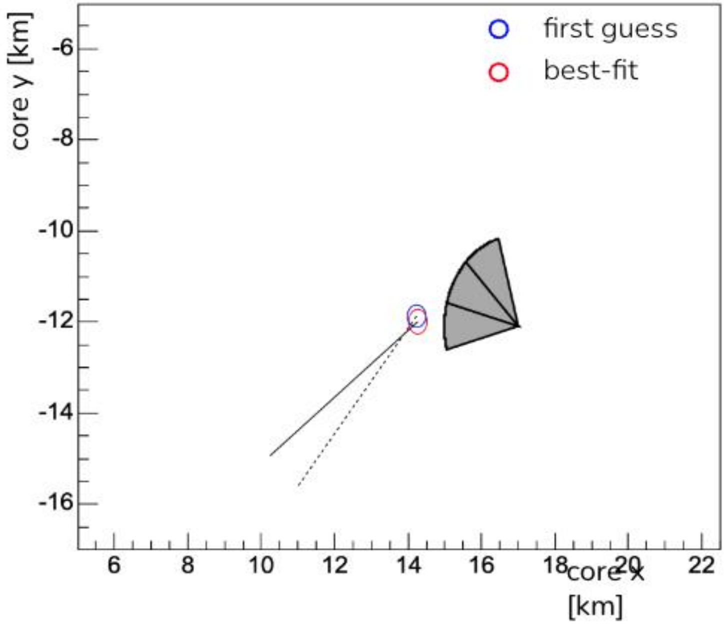


Event: 2018/05/15 09:27:21

	Auger-Mono	FAST
Energy [EeV]	19.05	18.15 ± 0.8
$X_{\max}$ [g/cm^2]	866	903 ± 17
Zenith [deg]	54.5	63.6 ± 0.0003
Azimuth [deg]	-170.4	-170.7 ± 0.01
Core x [m]	9270	-9271 ± 1
Core y [m]	-8770	-8769 ± 0.2

Example events - TA event 2





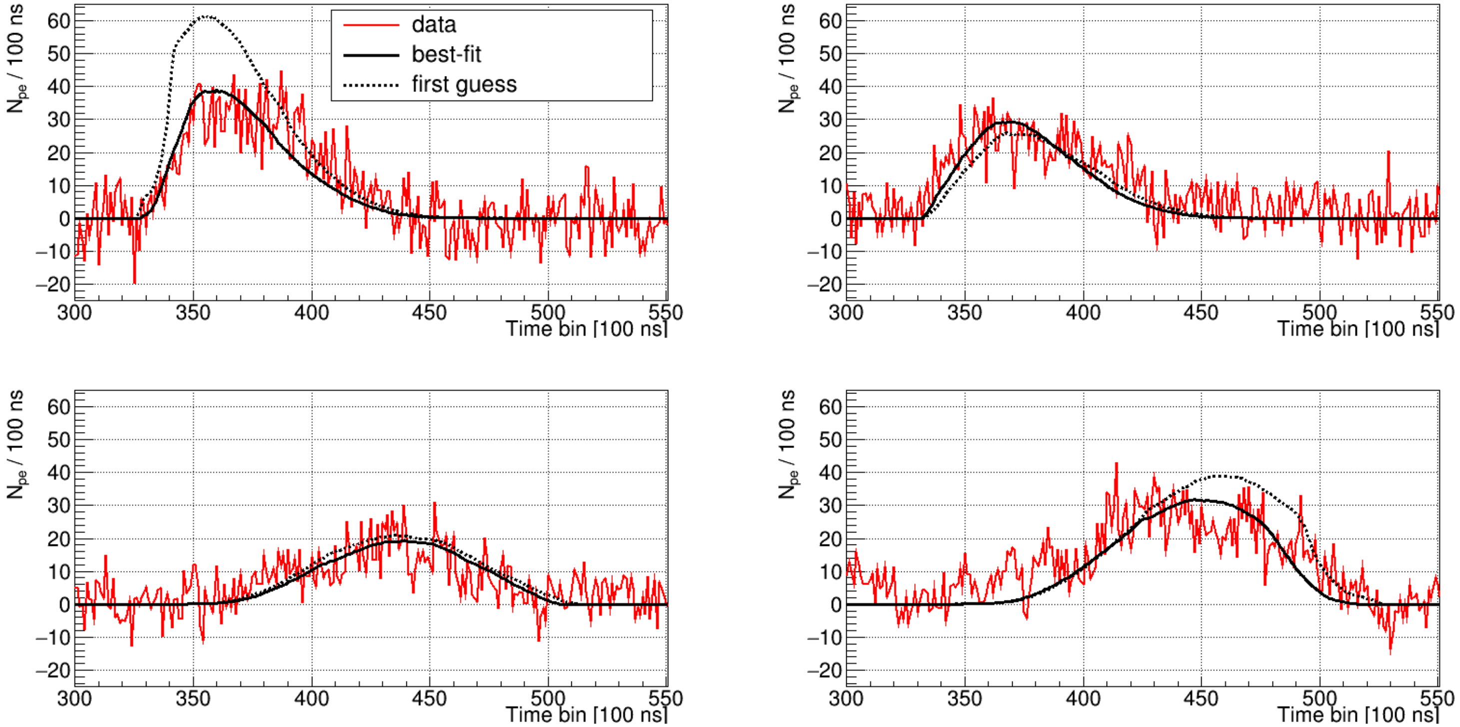
Preliminary result

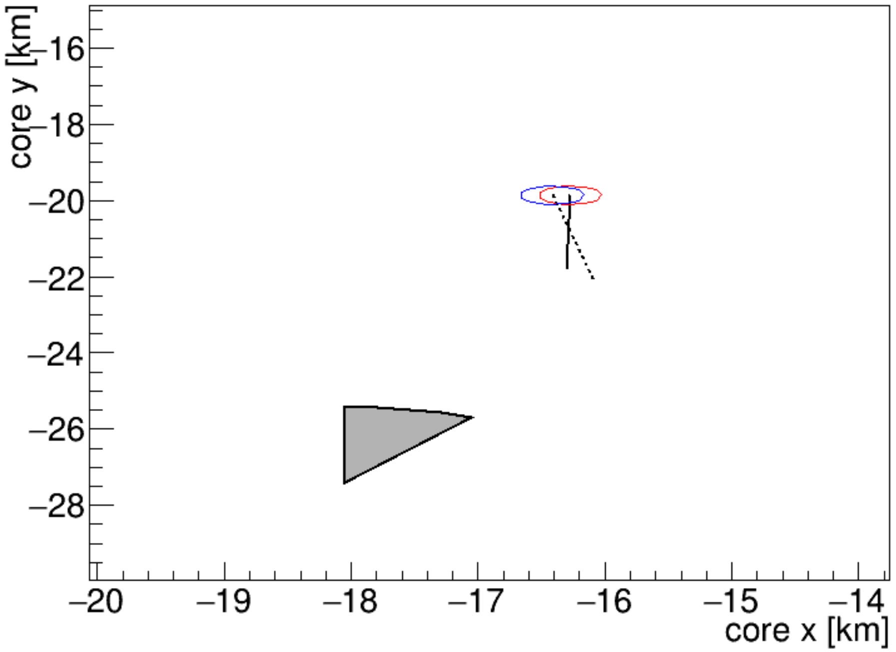
Event: 2019/01/11 06:30:01

	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

Example events - Auger event 1

[Auger event display here]



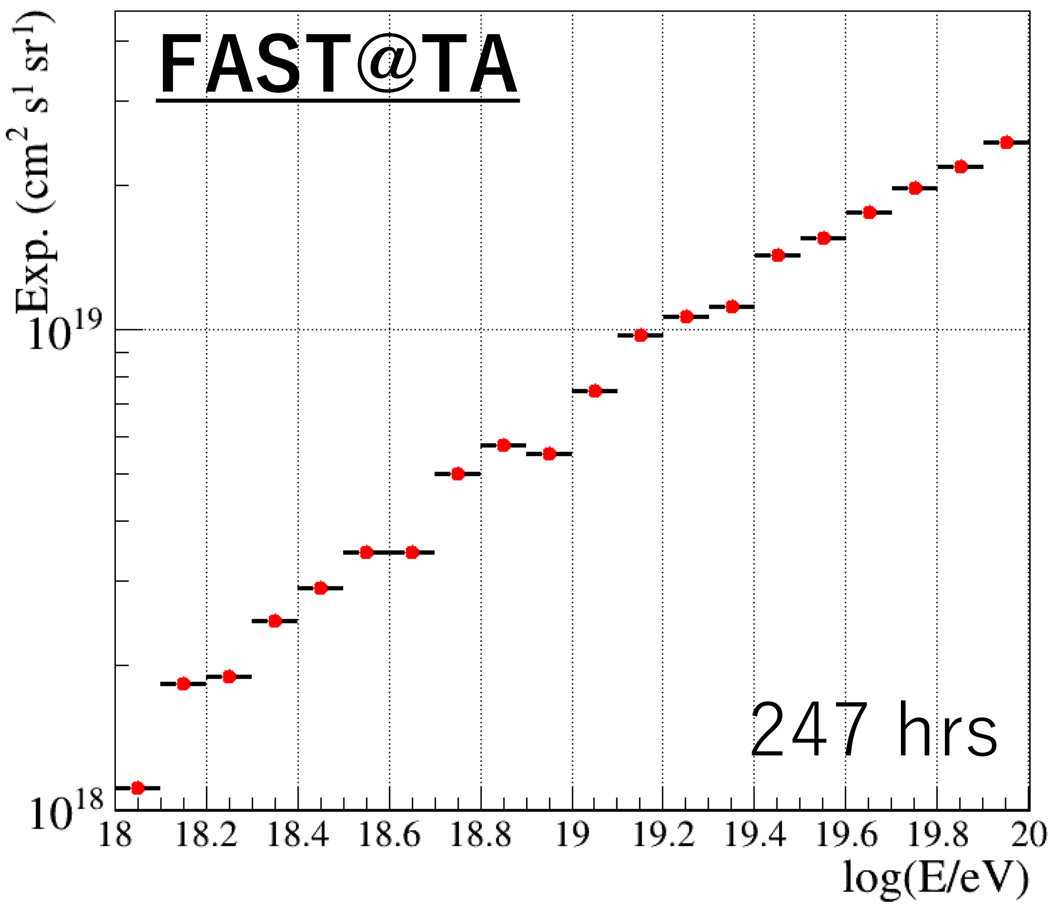


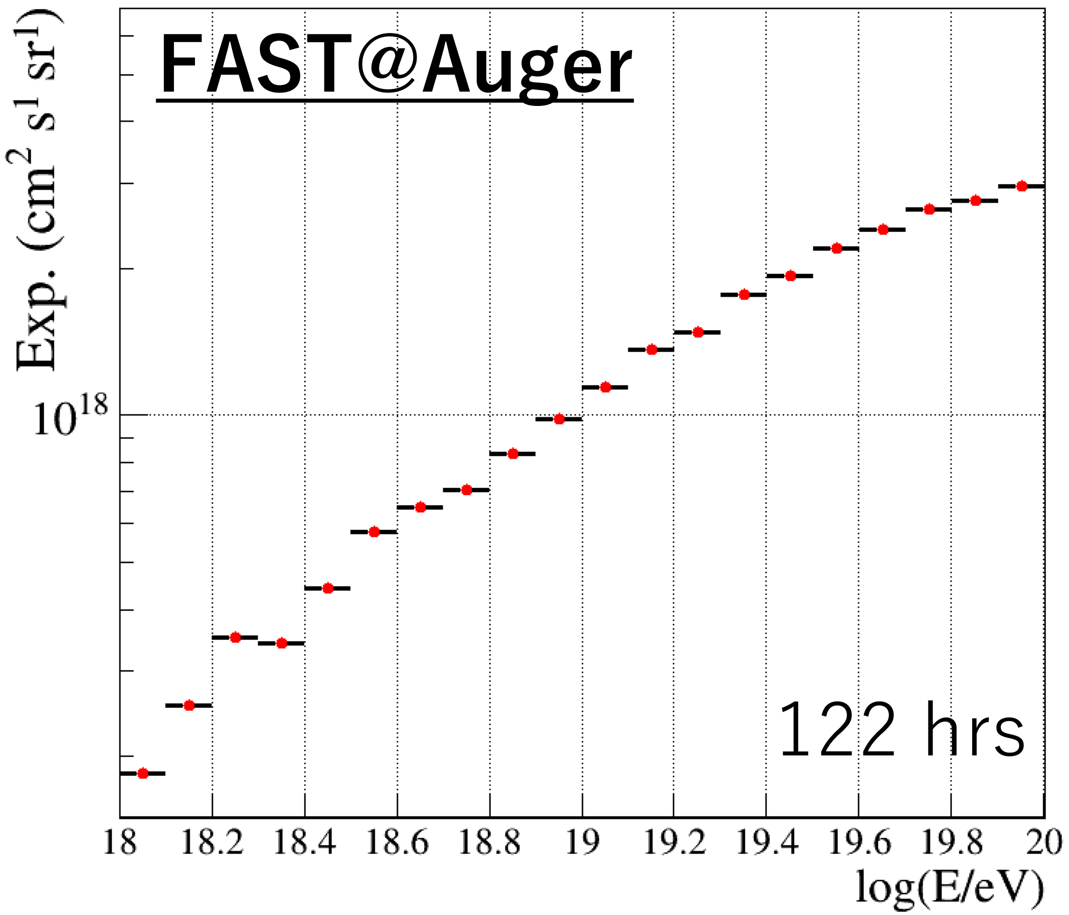
Event: 2022/10/21 01:57:26

	Auger-Mono	FAST
Energy [EeV]	13.8	11.59 ± 0.5
$X_{\max}$ [g/cm^2]	782	757 ± 24
Zenith [deg]	27.2	22.5 ± 0.003
Azimuth [deg]	-81.8	-90.8 ± 0.8
Core x [m]	-16414	-16273 ± 25
Core y [m]	-19859	-19859 ± 3

Exposure calculation

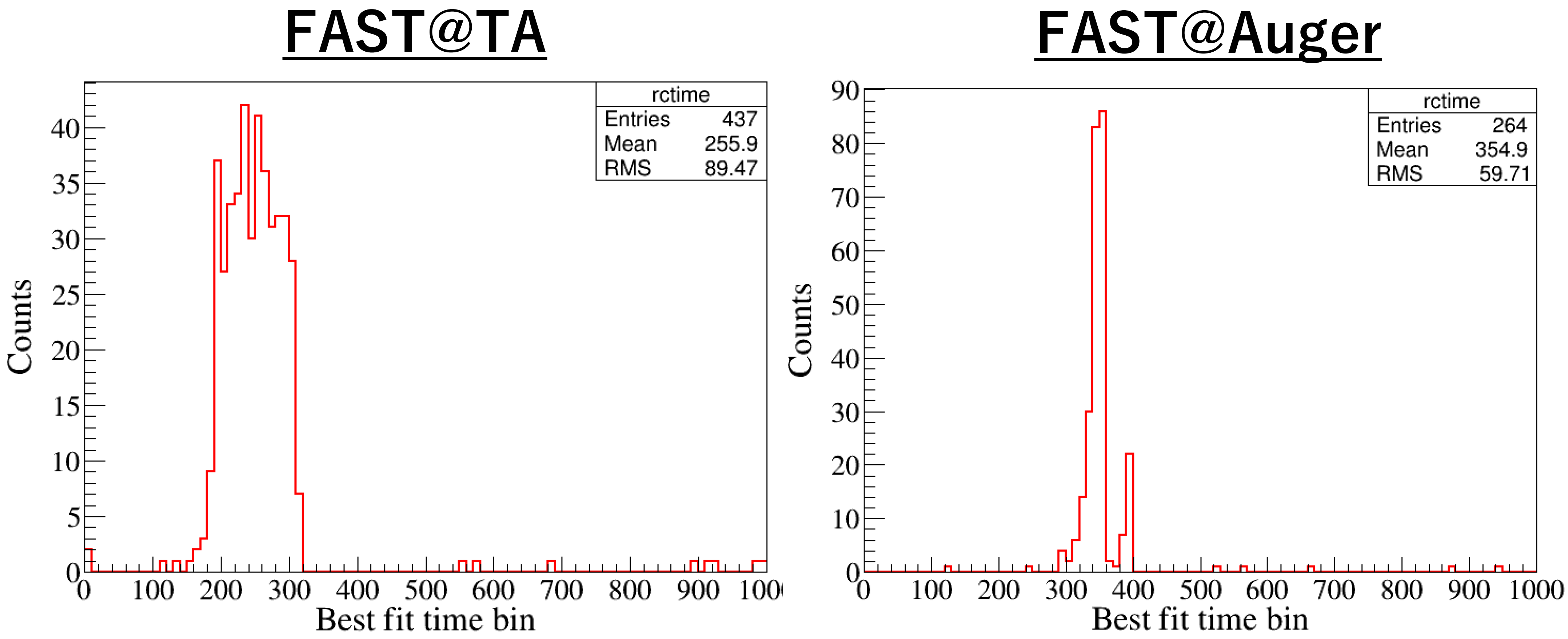
Calculated using MC data set used in previous data/MC comparison





Reconstruction results - extra

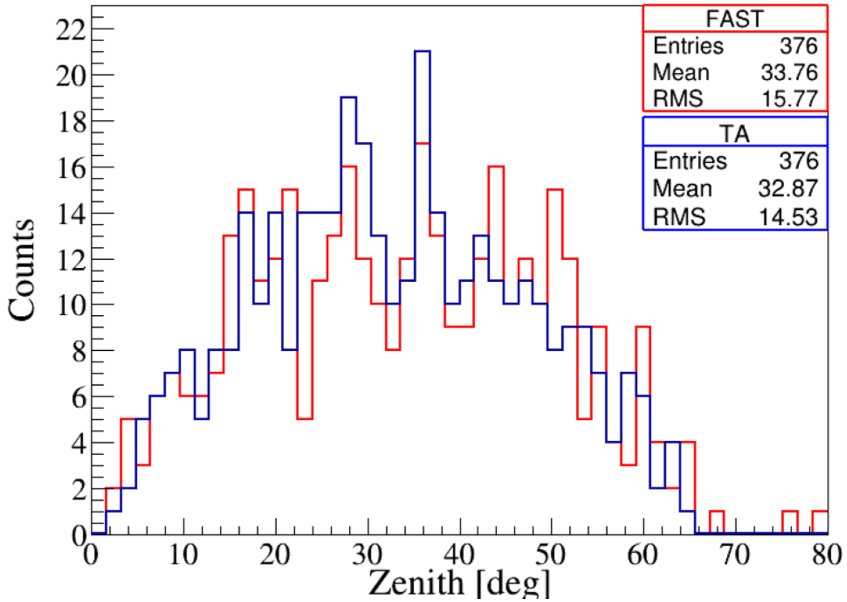
Best fit time bin

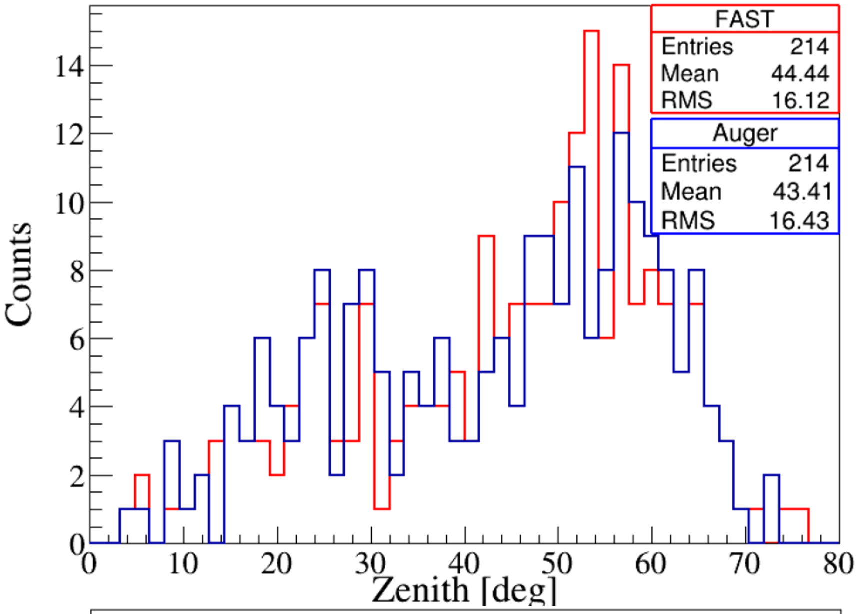


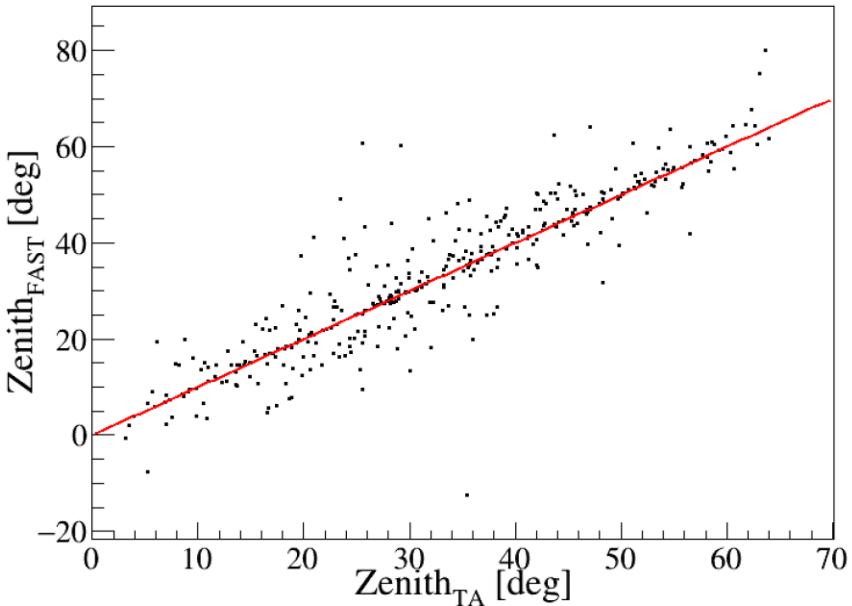
Reconstruction results - extra

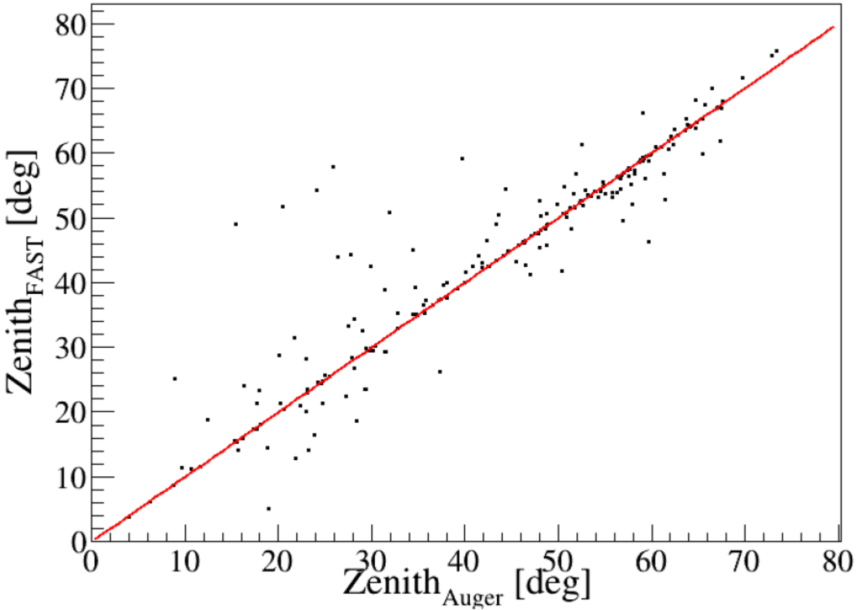
FAST@TA **FAST@Auger**

Zenith







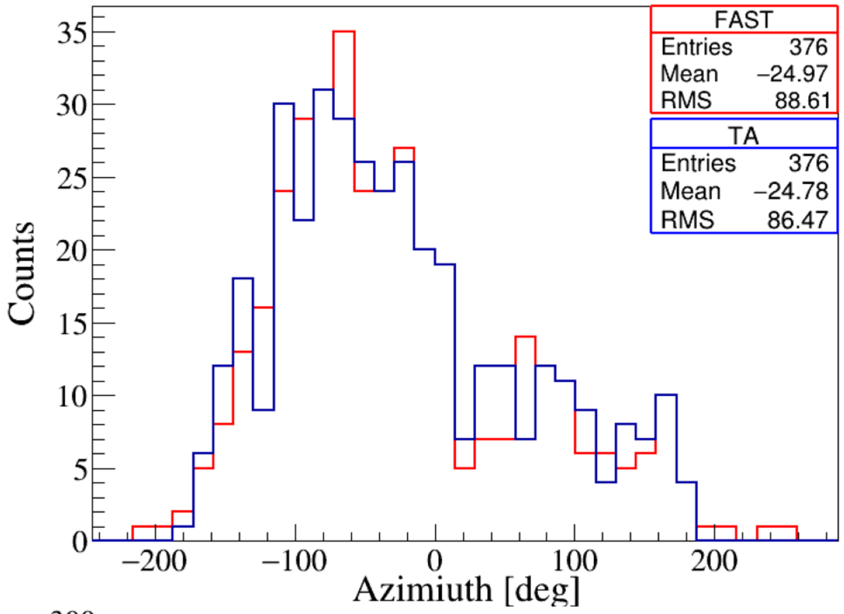


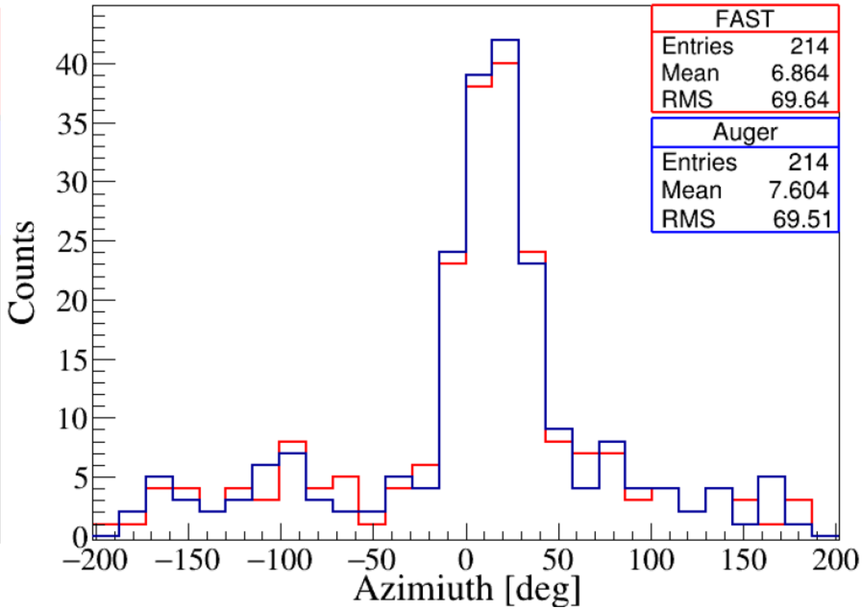
Reconstruction results - extra

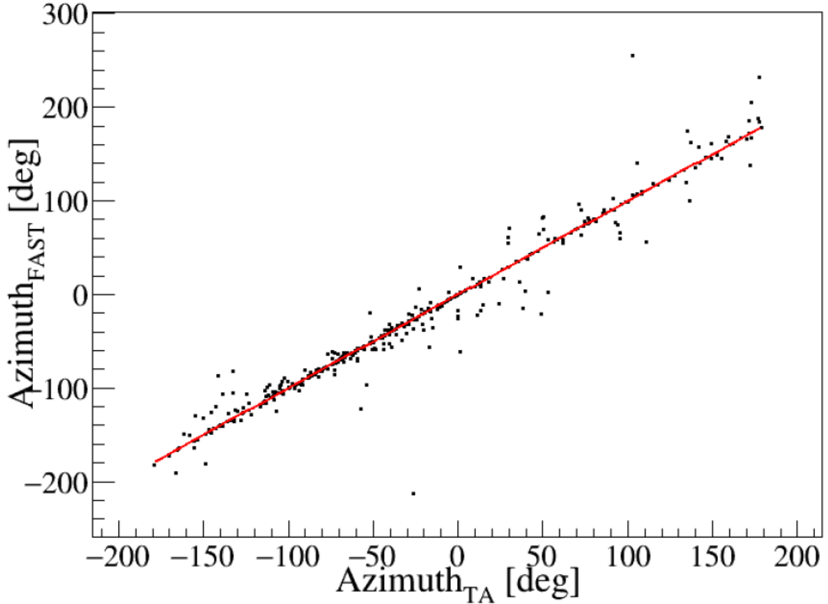
FAST@TA

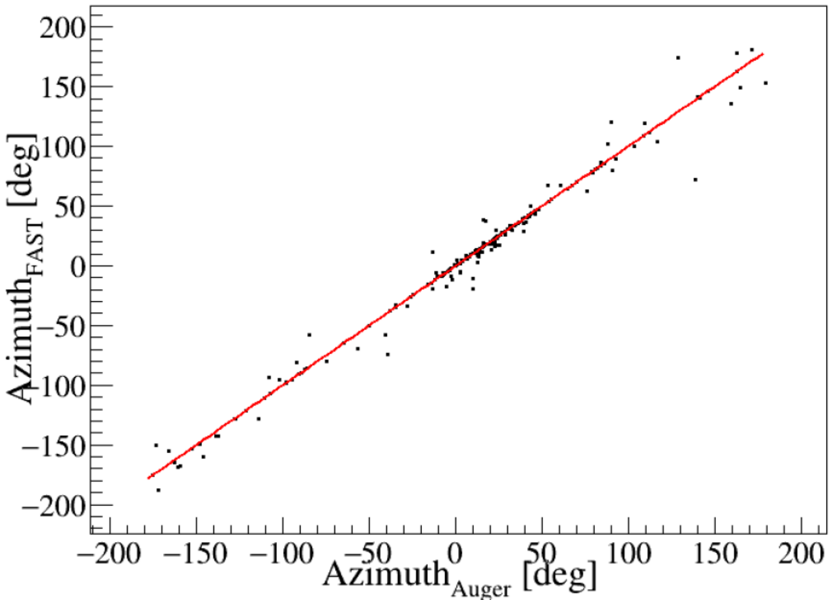
FAST@Auger

Azimuth





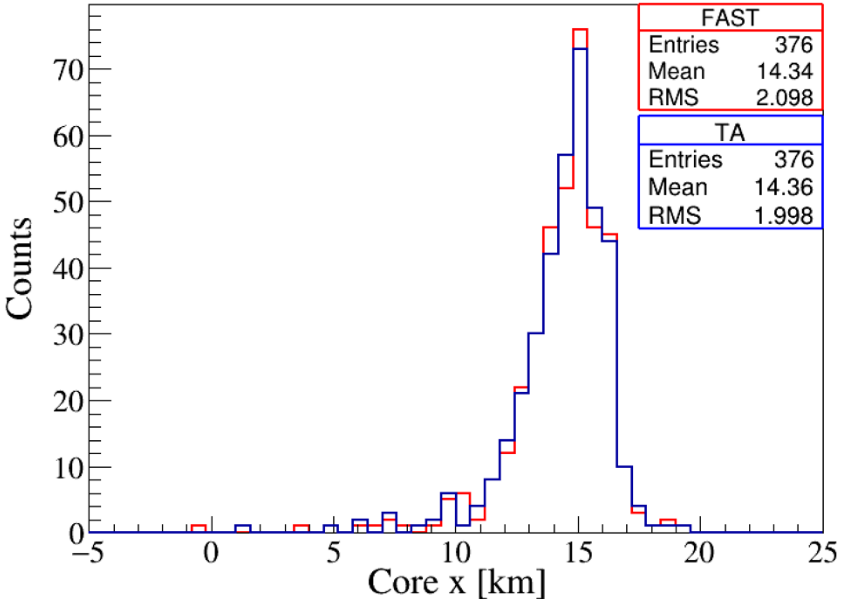




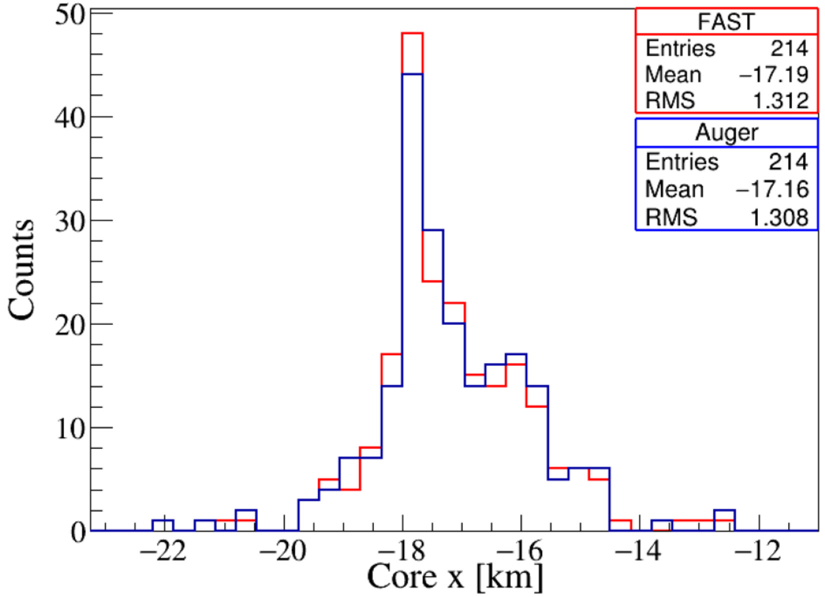
Reconstruction results - extra

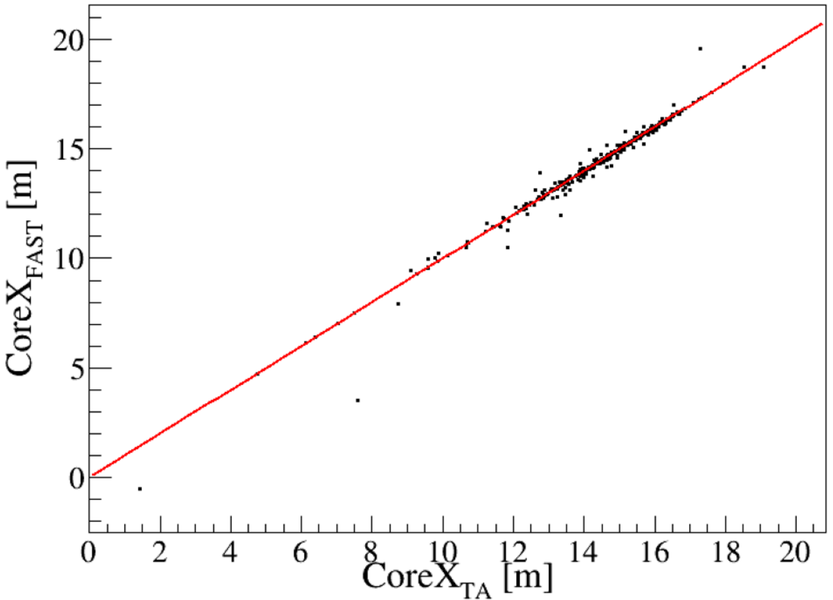
Core X

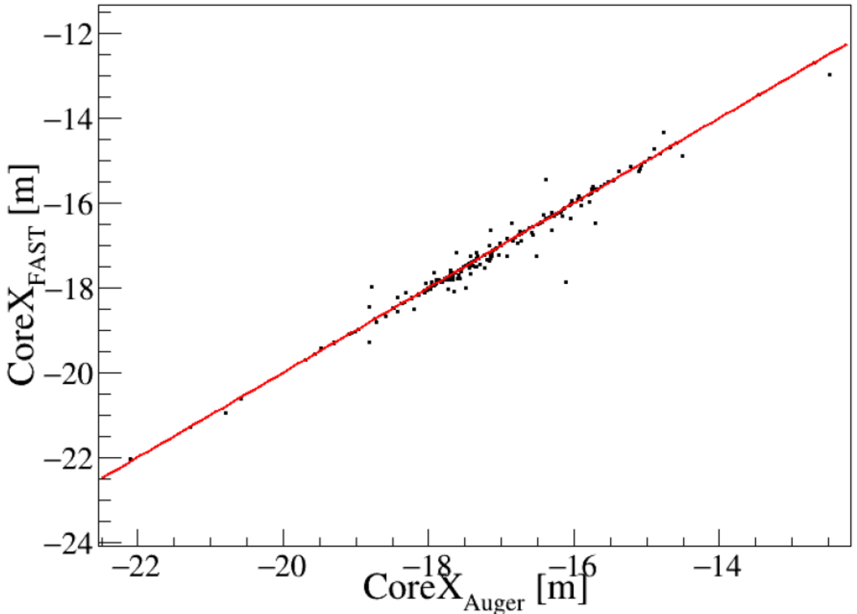
FAST@TA



FAST@Auger



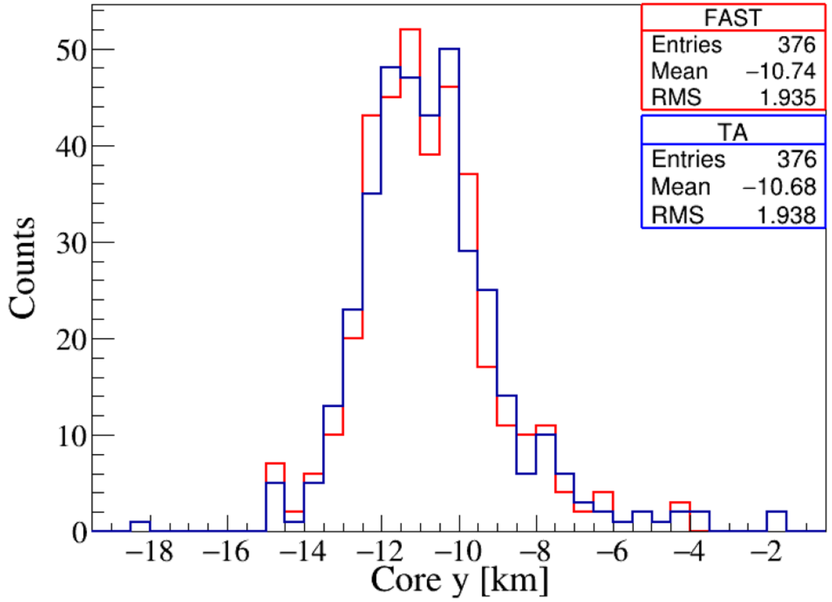


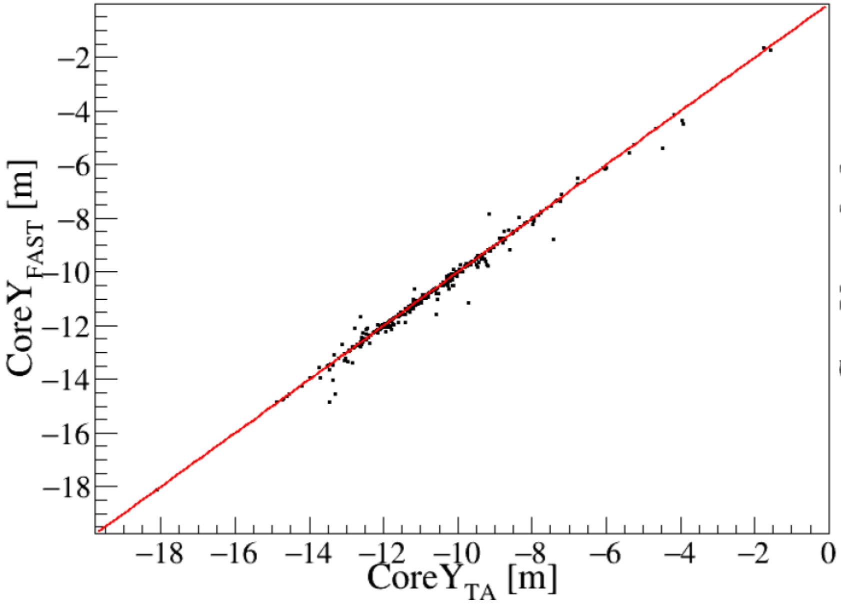


Reconstruction results - extra

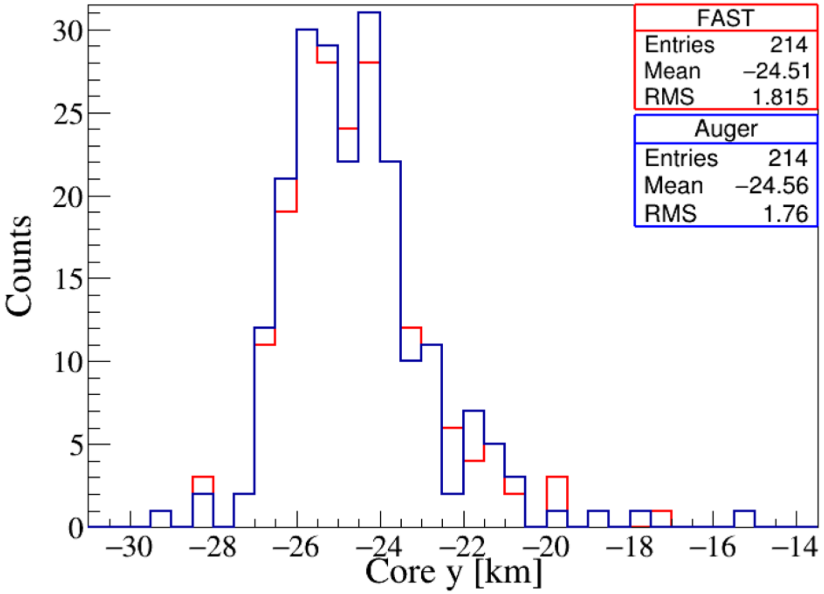
Core Y

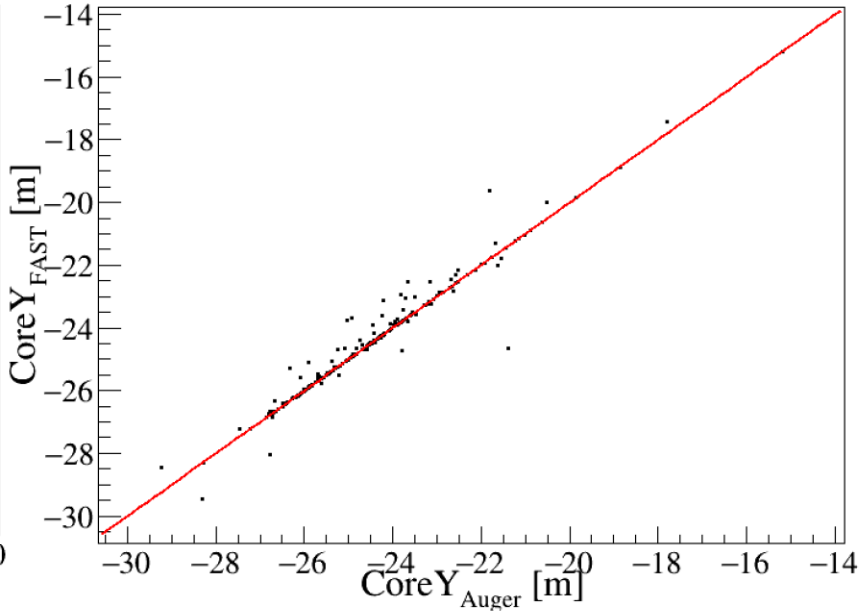
FAST@TA





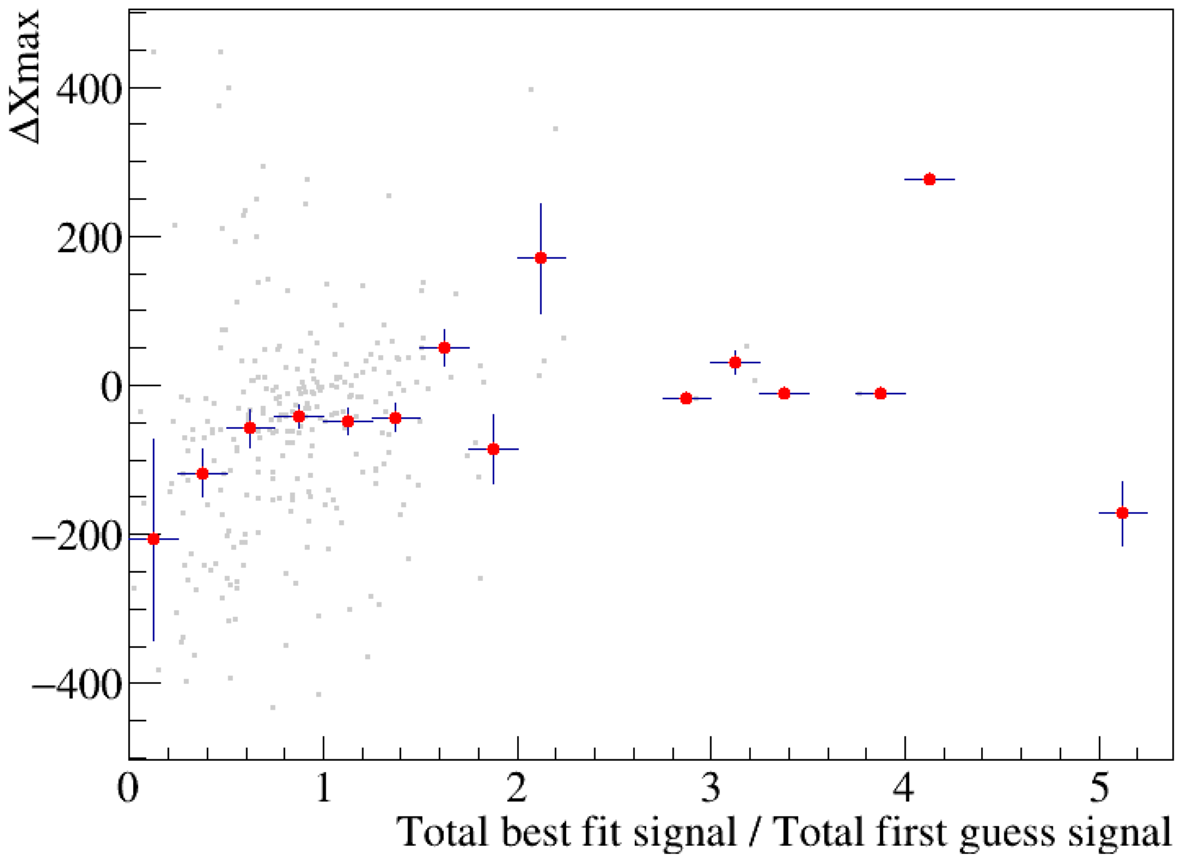
FAST@Auger



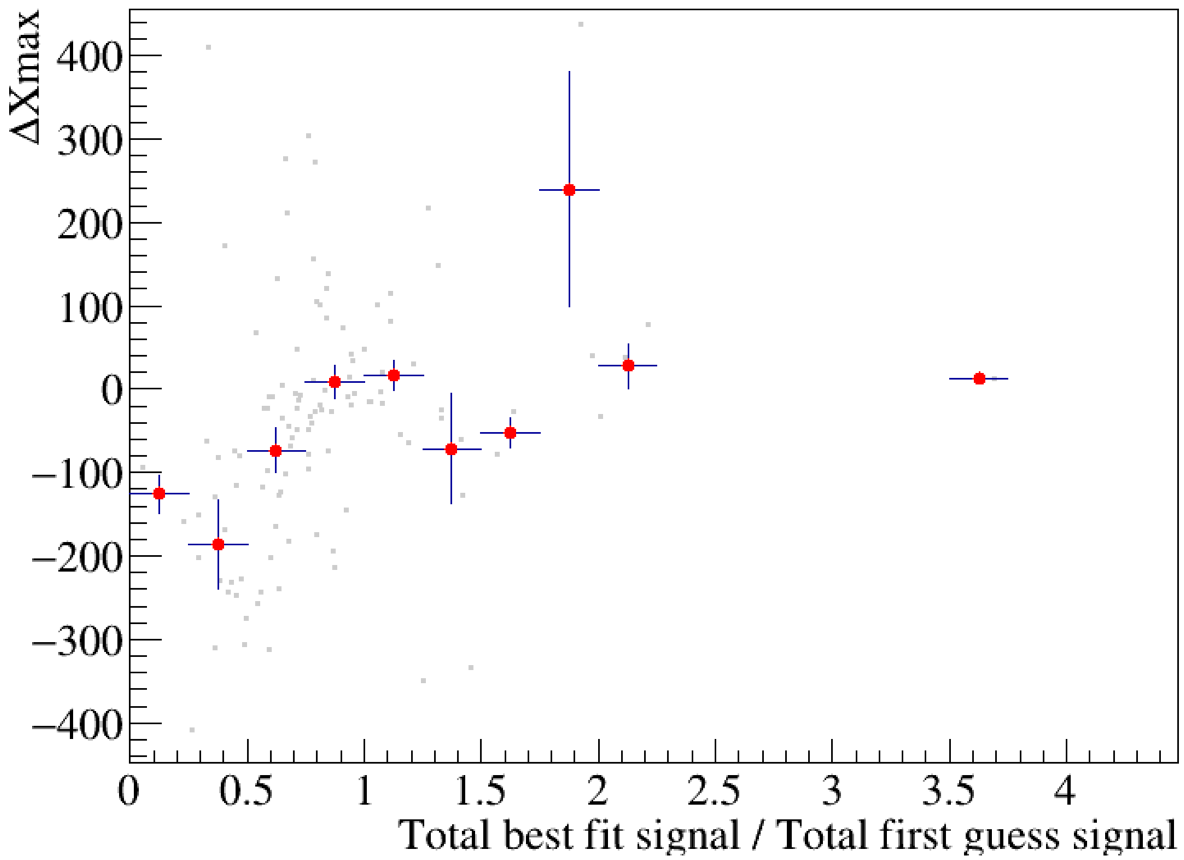


Xmax bias – signal difference

FAST@TA



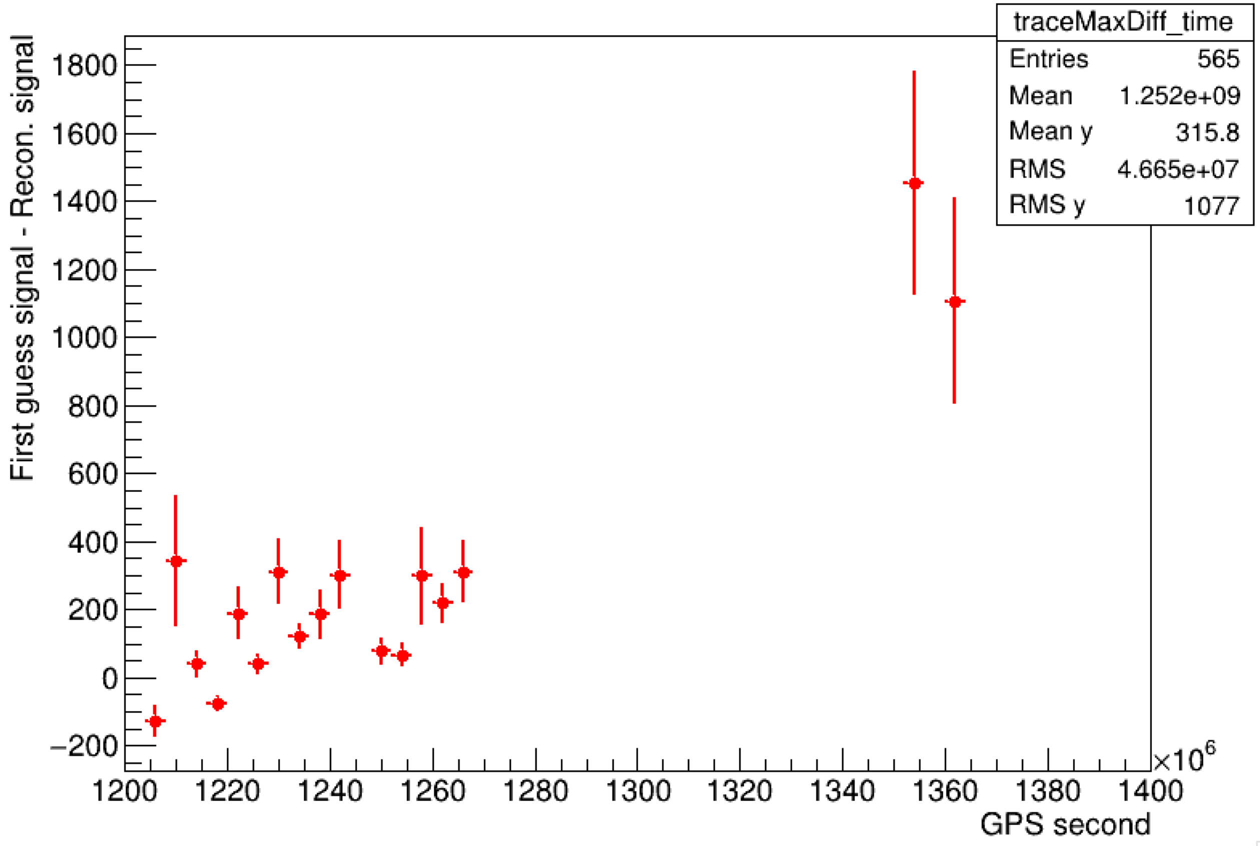
FAST@Auger



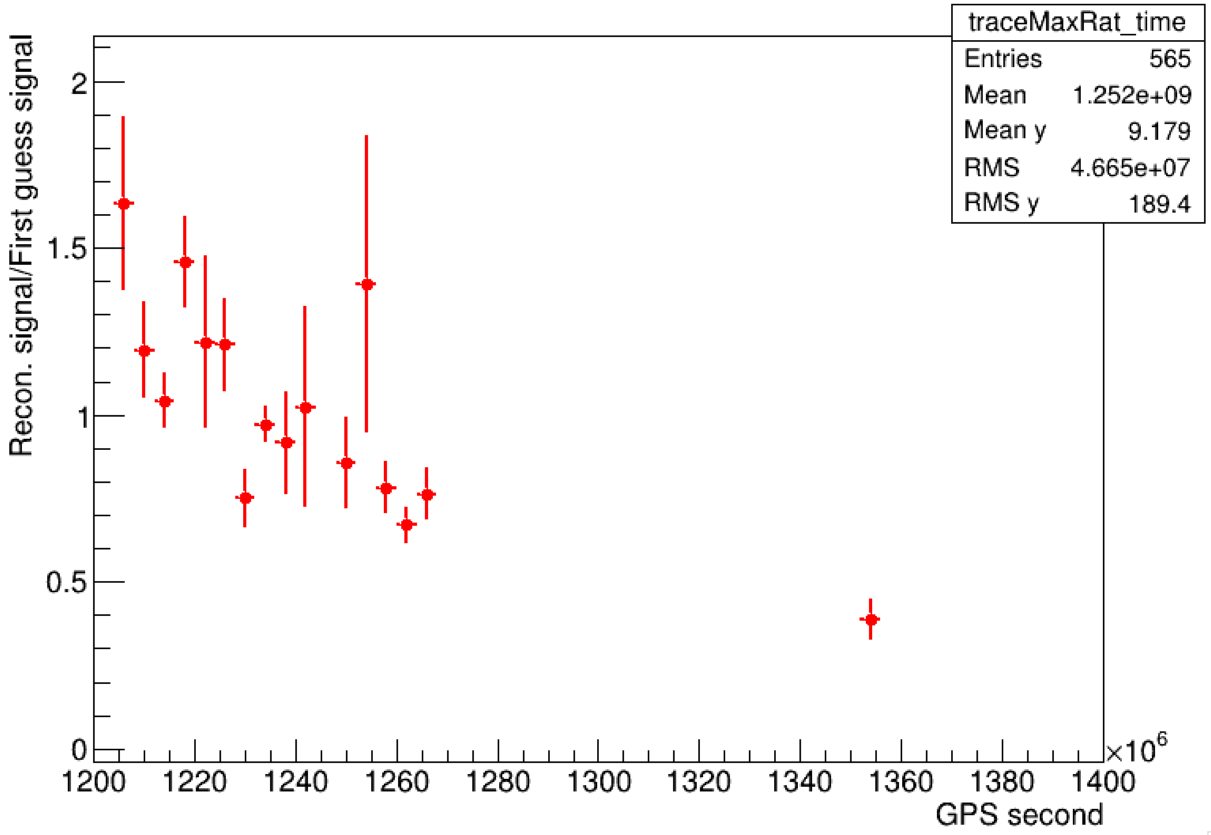
Xmax bias – signal difference

FAST@TA

Difference



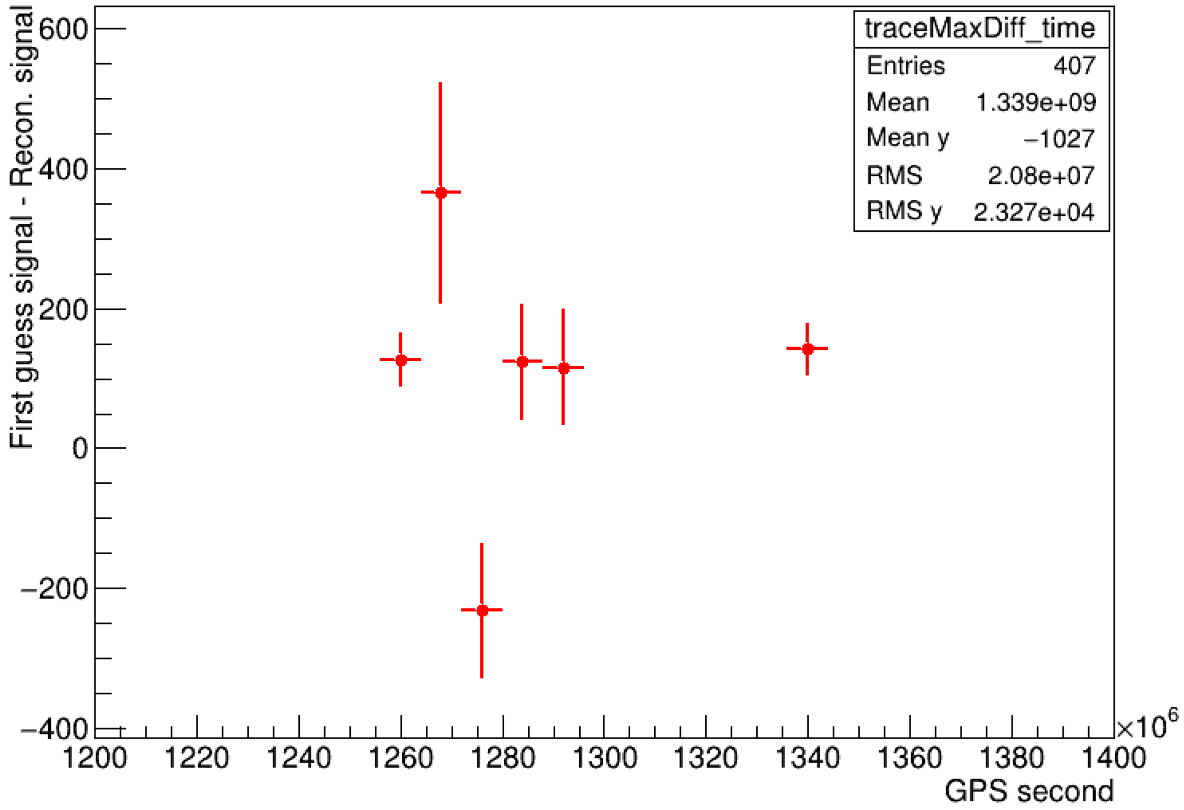
Ratio



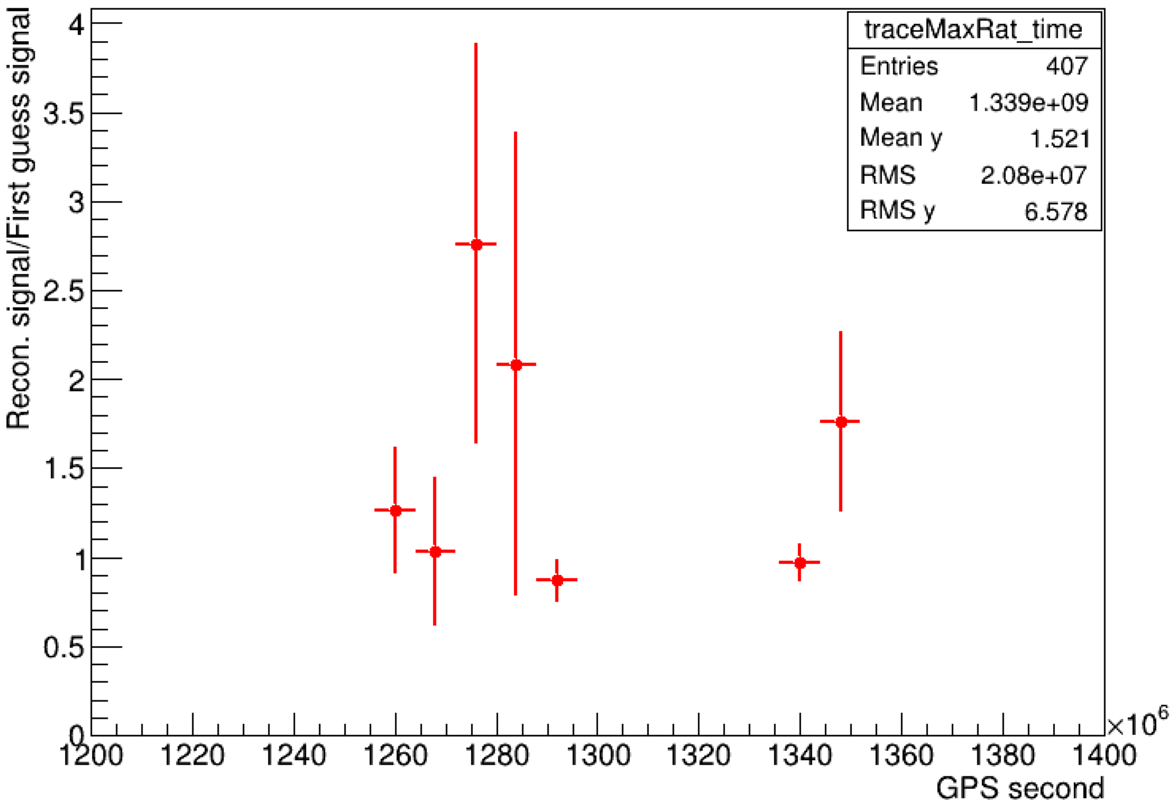
Xmax bias – signal difference

FAST@Auger

Difference



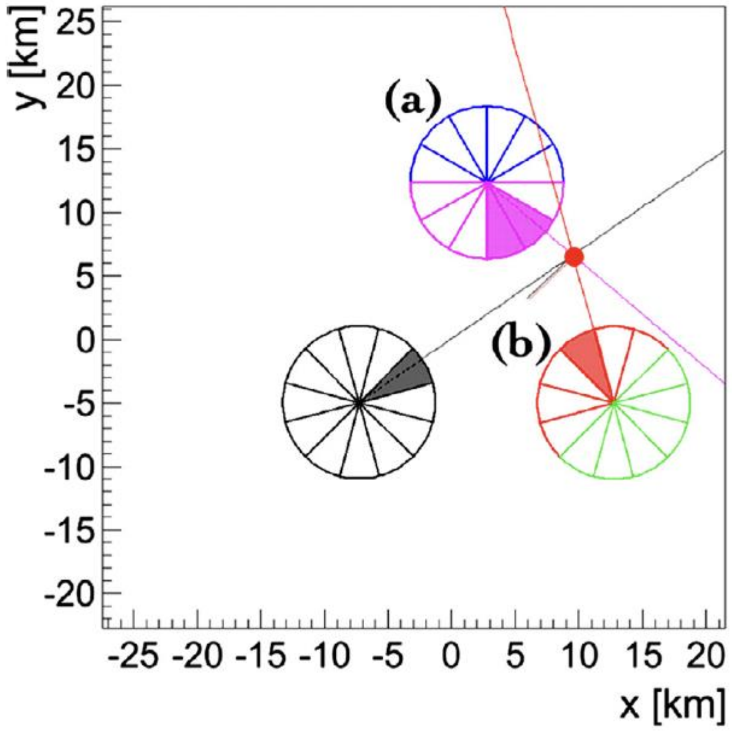
Ratio

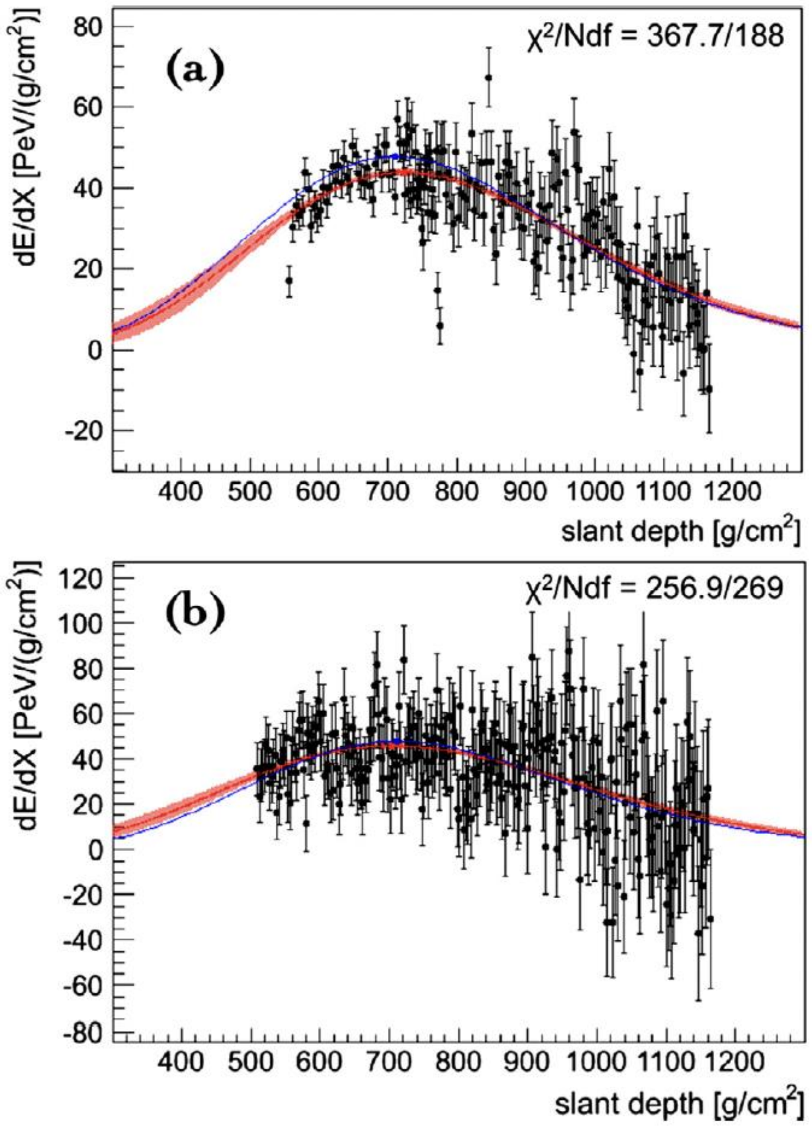


Gaisser Hillas reconstruction

Need geometry!

Most likely only obtainable with stereo observation

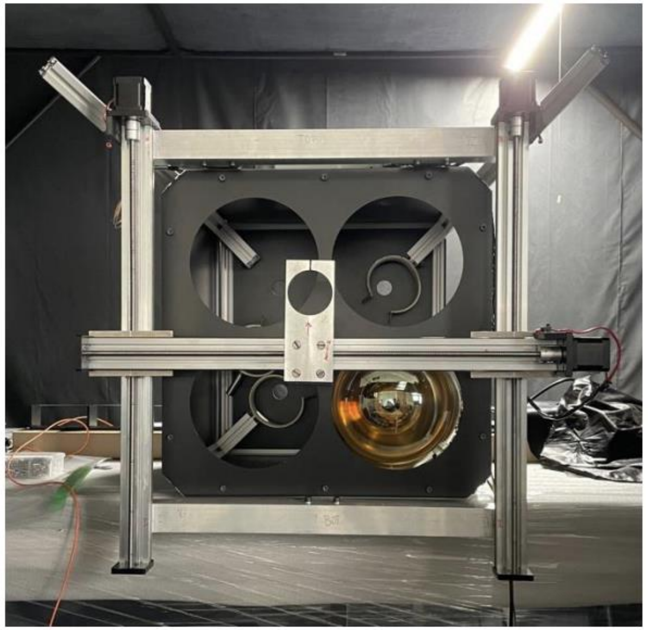




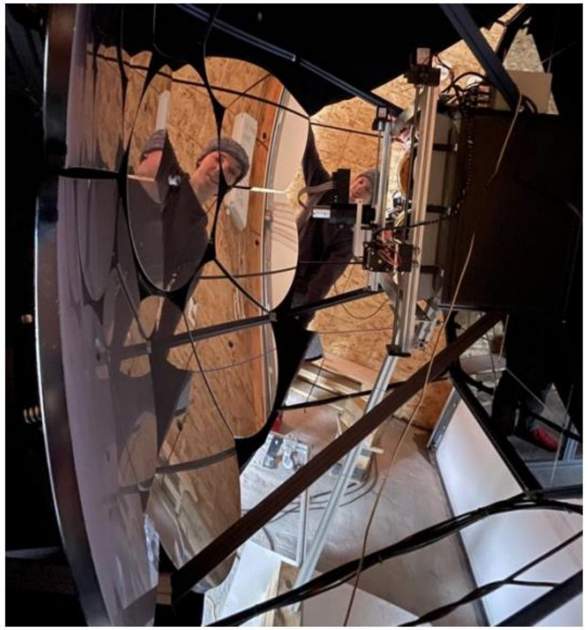
PMT scan - measurement setup

- XY scanner
  - **1 mm** by stepping motor
  - Control by serial communication
- LED flasher
  - Wavelength (400 nm)
  - Spot size: **1 cm** circle
  - Pulse width: 10us
  - Trigger: 100 Hz
  - Intensity: set to 8000 (*)
- Oscilloscope
  - PicoScope 3400D-MSO
  - External trigger from flasher
- PC

XY scanner

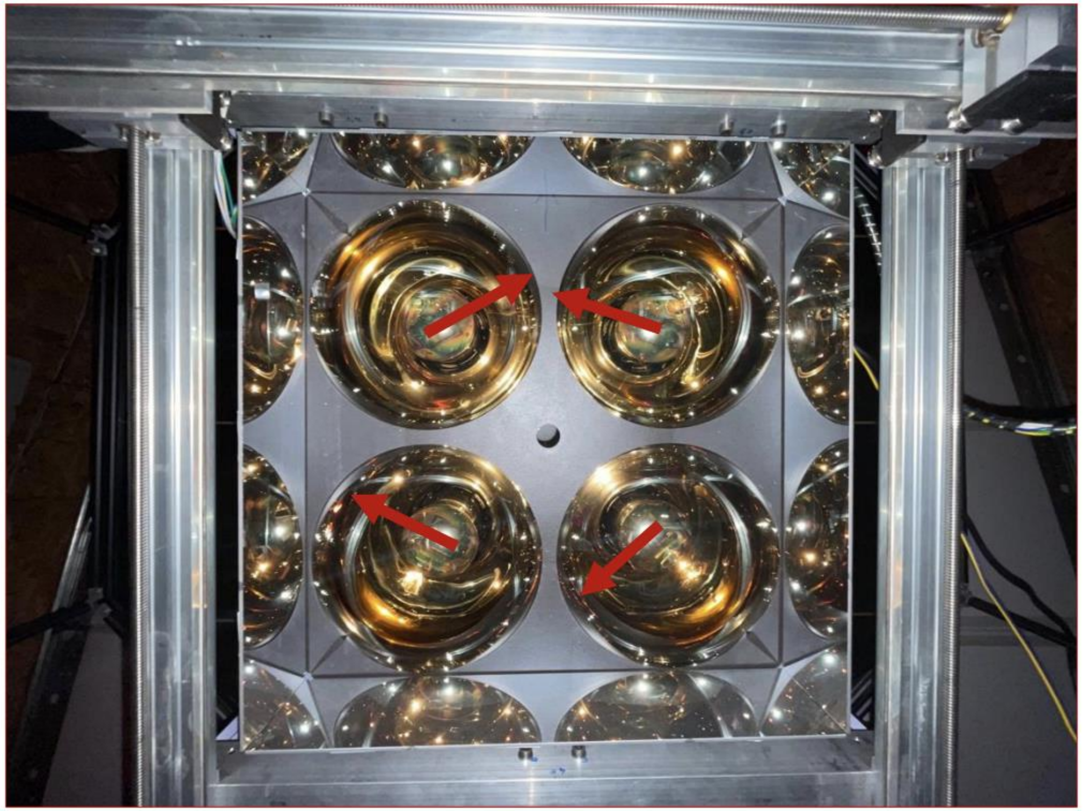


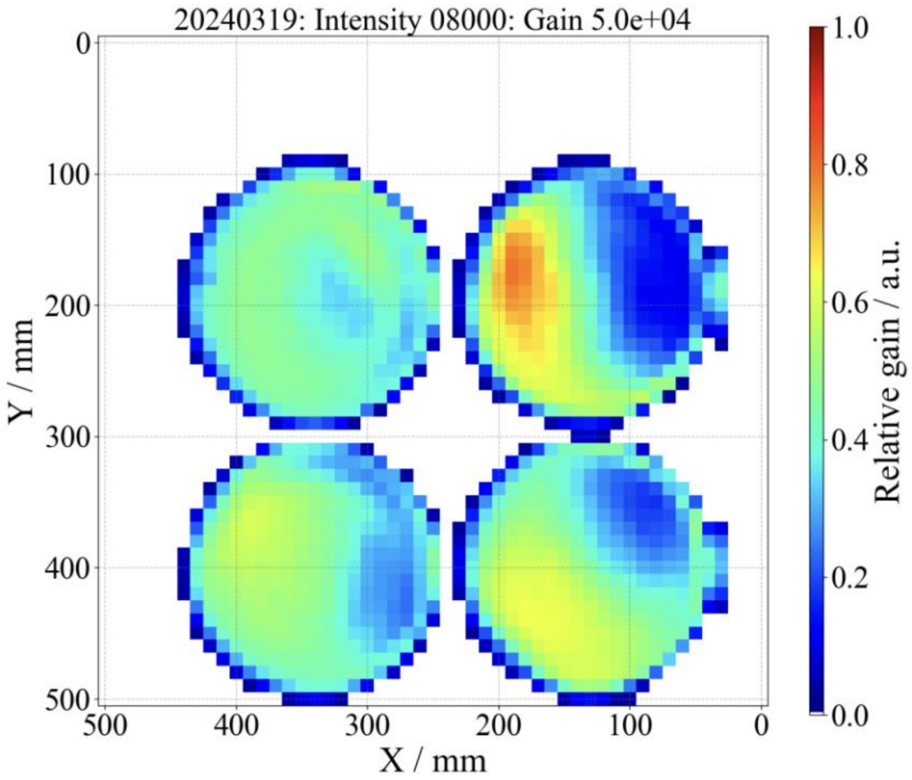
XY scanner on FAST2



LED flasher
collimator

PMT scan – PMT alignment angle



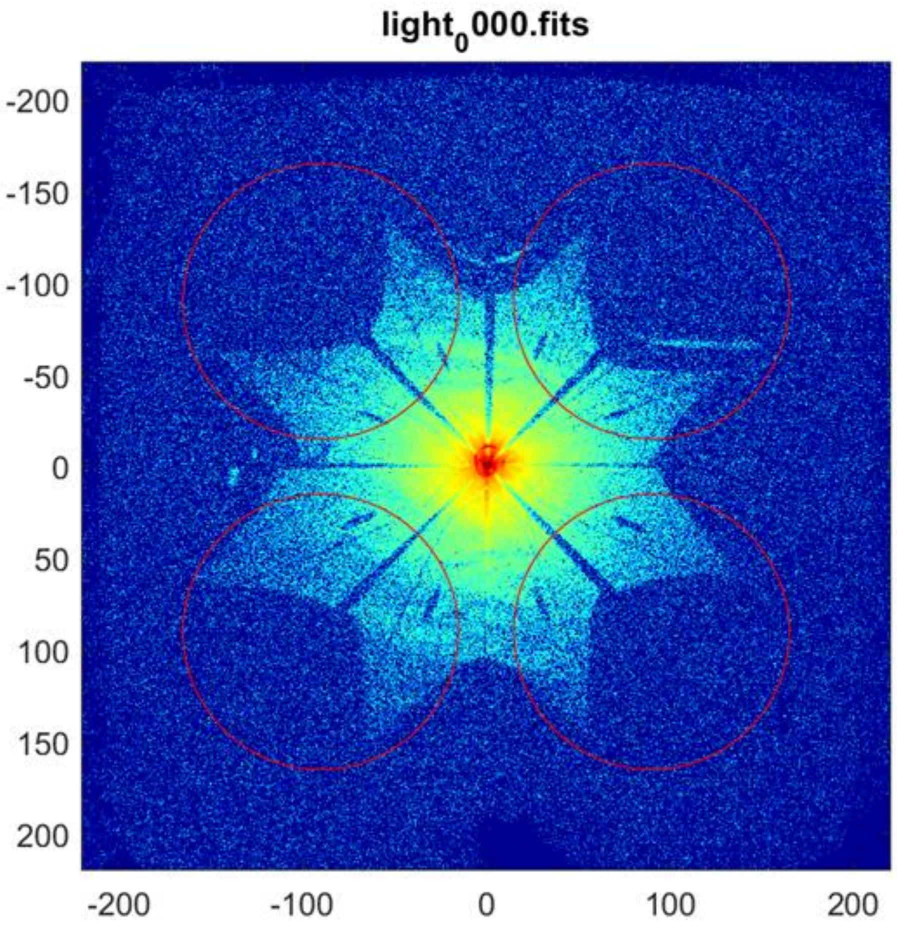


No clear conclusion as for today.

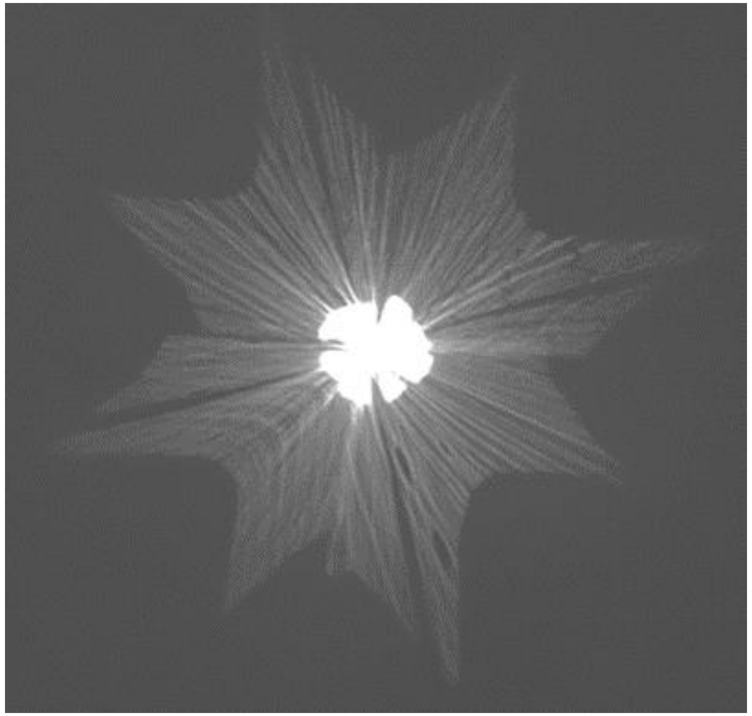
1st dynode direction is more efficient

FAST Field telescope PSF

9 segment – old design

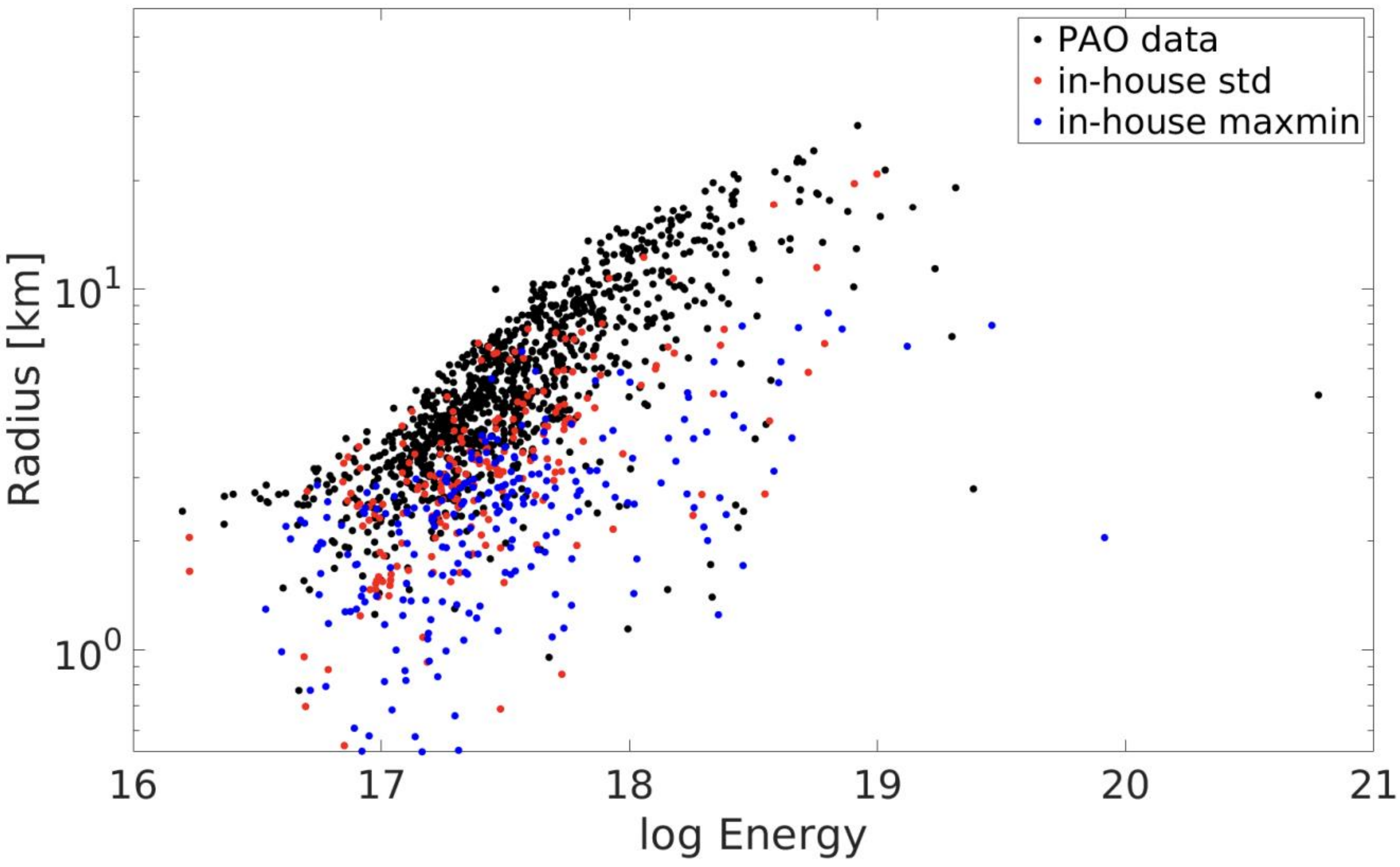


4 segment – new design

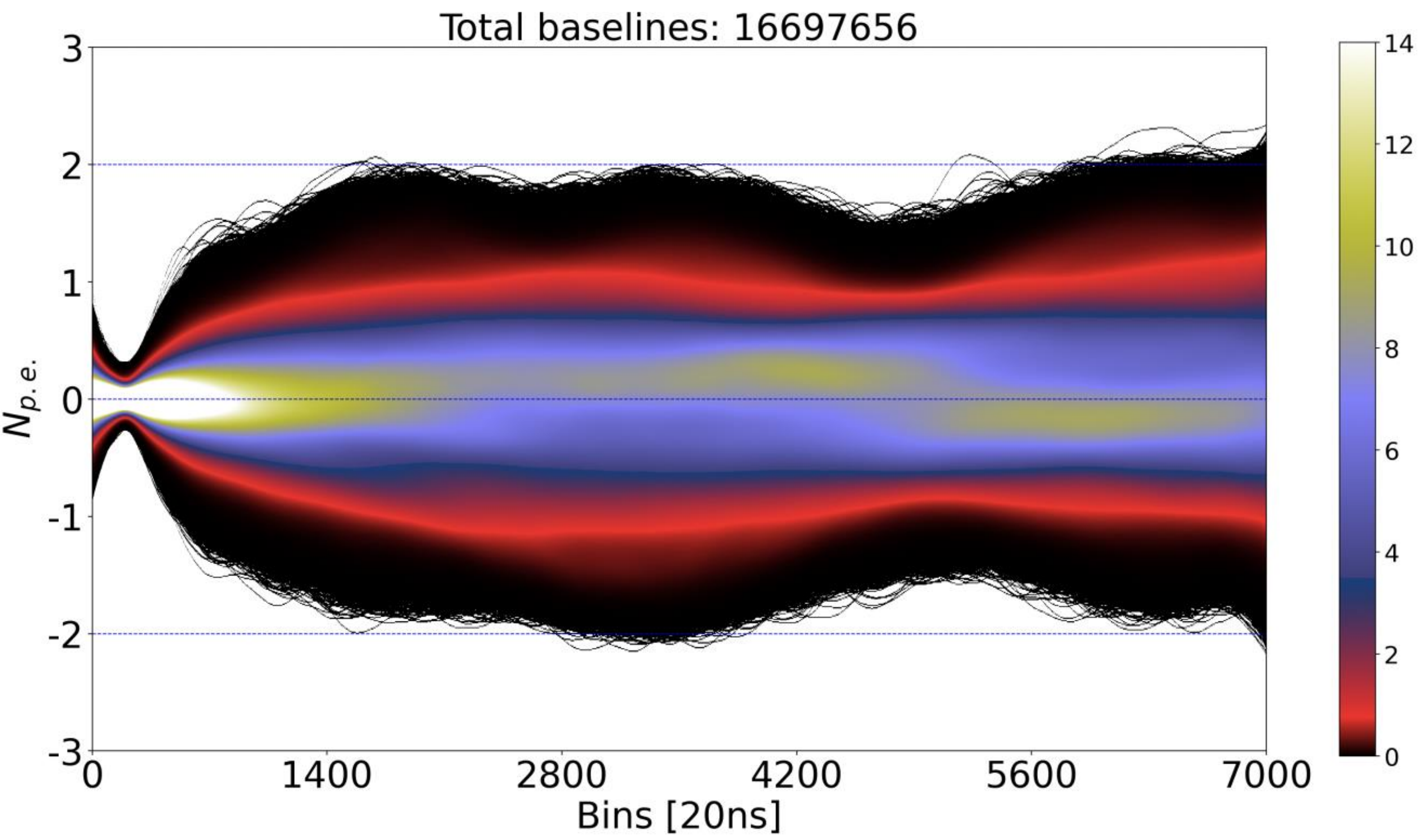


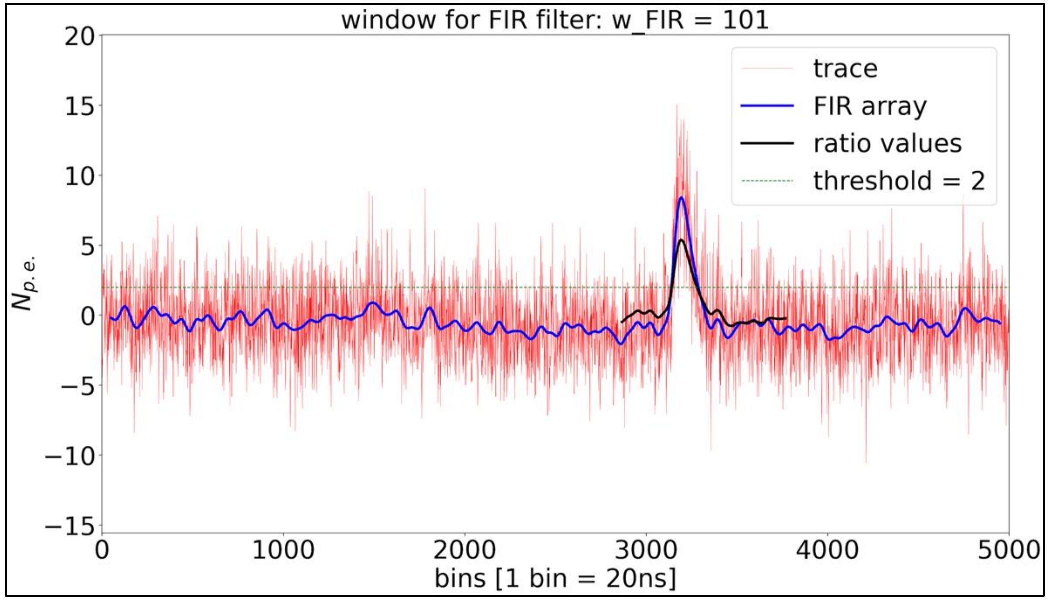
*(not to scale)

Signal detection – coincidence Energy vs. R_p

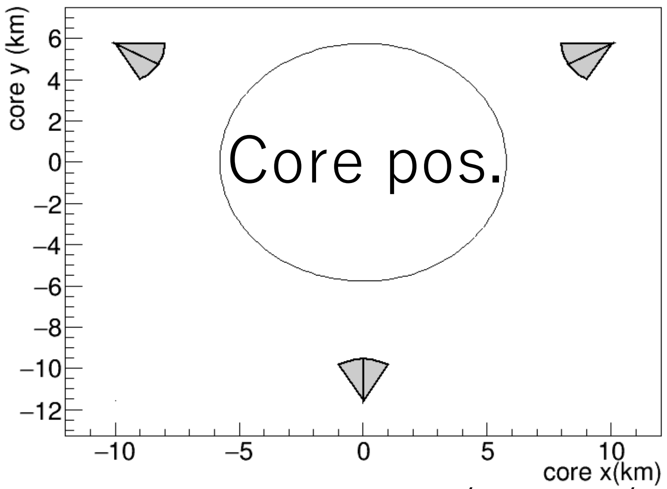


Signal detection – baseline estimation





Machine learning for FAST mini-array



Inputs: Pulse timing/height/integral from each PMT

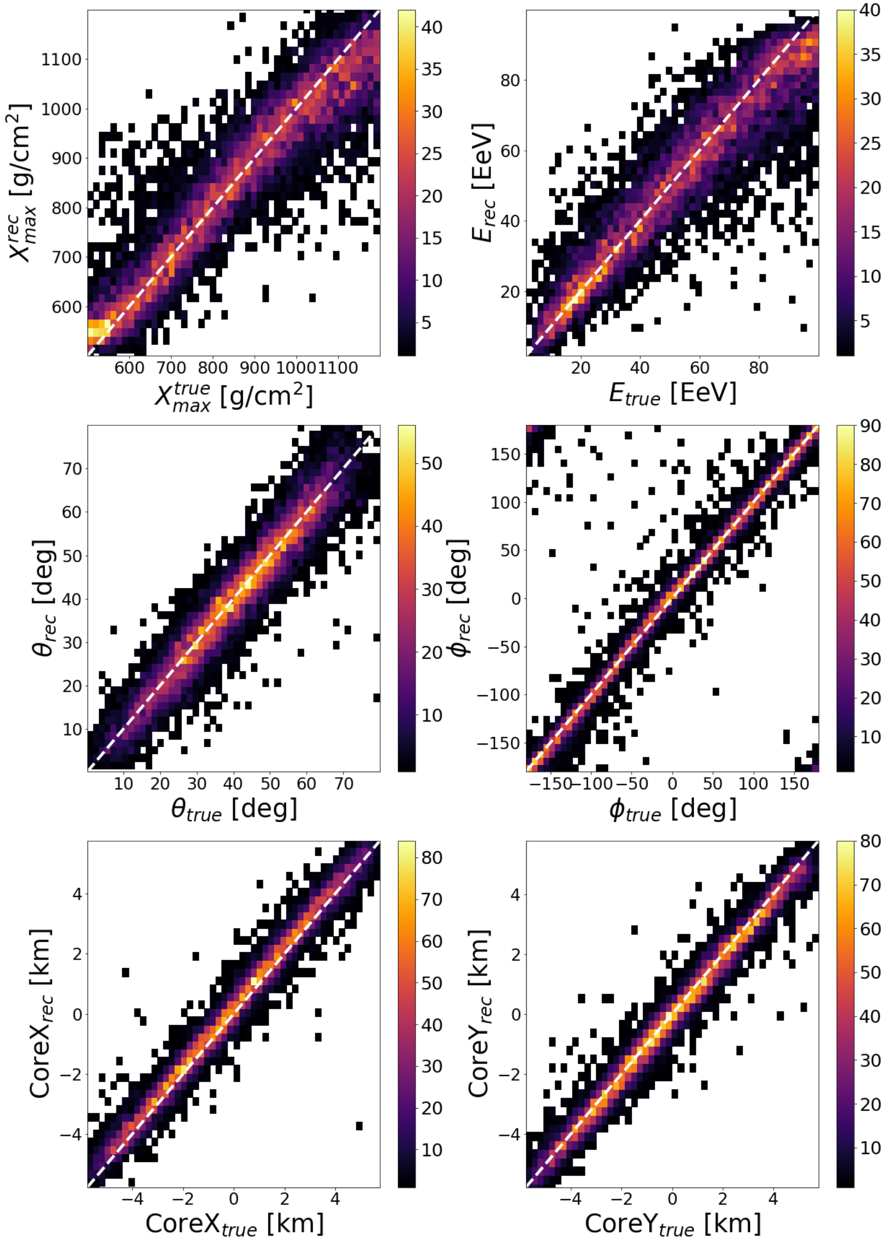
Training: 300,000 showers

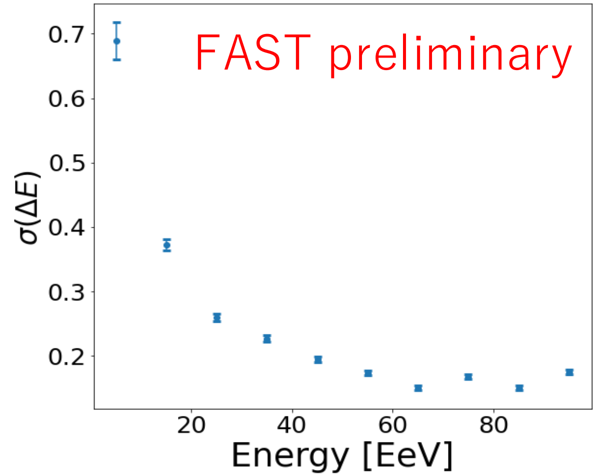
$X_{\max}$ 500 - 1200 g cm^{-2}

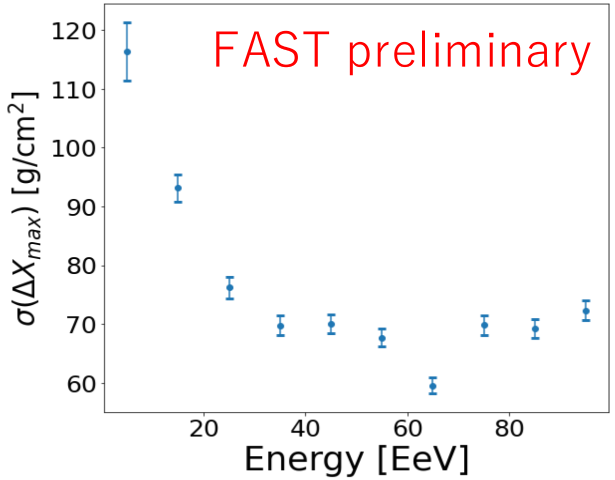
E 1 - 100 EeV

θ 0 - 80°

φ 0 - 360°







Testing: 10,000 showers

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

Core pos: Circle at (0,0), $r = 5773$ m

Rec. cuts: Rec. energy > 10^{18} eV
All three stations triggered

- Simple NN shows reasonable performance as first guess

Simulation flow

Use old version of Auger Offline software as simulation backbone. Have written specific modules for FAST.

Typical simulation…

- FASTProfileSimulatorCG
- FASTEventGeneratorCG
- ShowerLightSimulatorKG
- FASTSimulator
- FASTEventFileExporter

Xmax parameterisation

- From Blaess, 2018
- Parameterizations of EPOS, QGSJetII.04 and Sybil Xmax distributions for 4 primary mass groups (p, He, CNO, Fe)
- When Xmax is generated, choose mass group based on fractions provided (typically [0.25, 0.25, 0.25, 0.25]), then based on mass group chosen and energy randomly sample Xmax from appropriate distribution.