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

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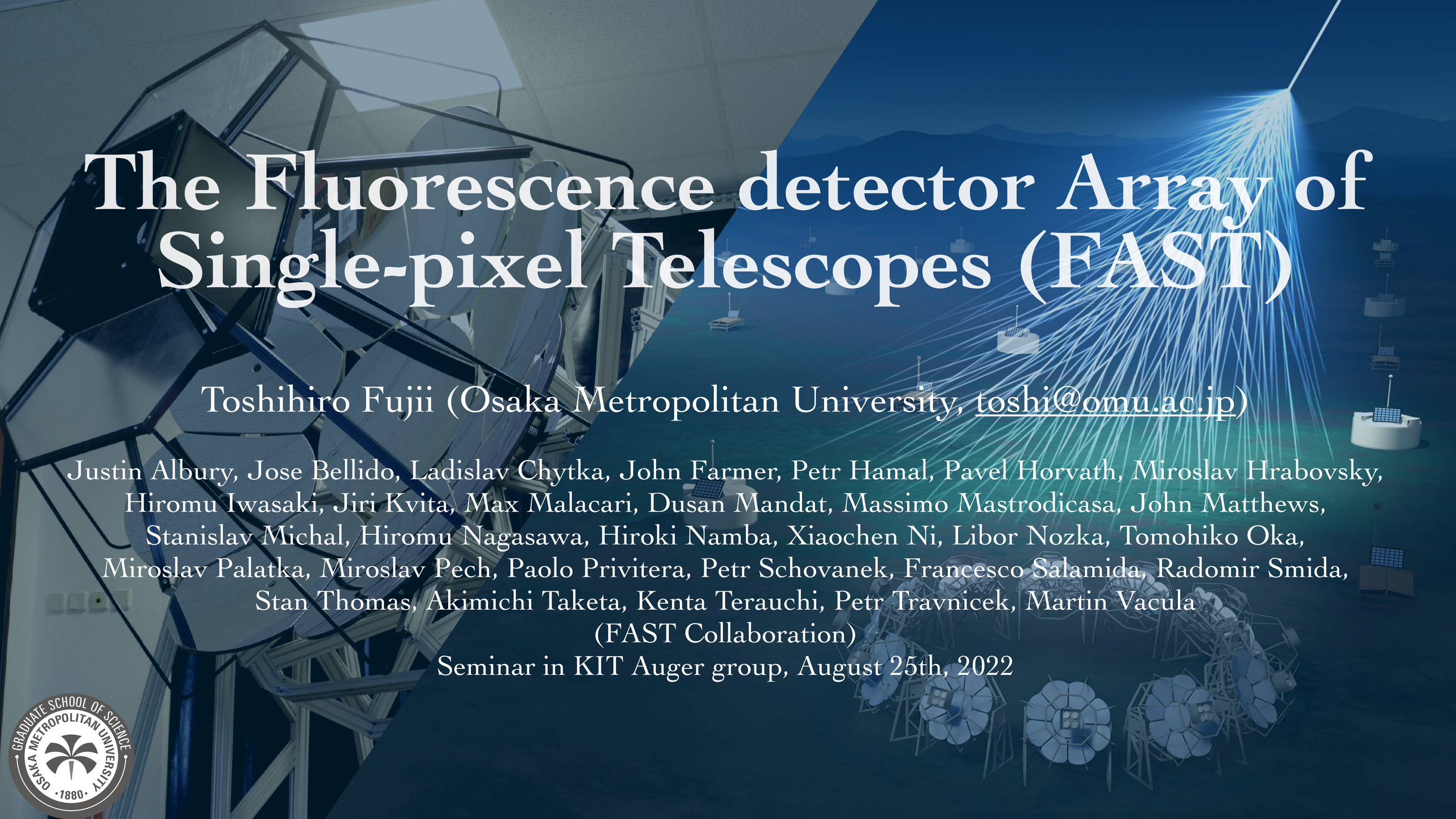
Justin Albury, Jose Bellido, Ladislav Chytka, John Farmer, Petr Hamal, Pavel Horvath, Miroslav Hrabovsky, Hiromu Iwasaki, Jiri Kvita, Max Malacari, Dusan Mandat, Massimo Mastrodicasa, John Matthews, Stanislav Michal, Hiromu Nagasawa, Hiroki Namba, Xiaochen Ni, Libor Nozka, Tomohiko Oka, Miroslav Palatka, Miroslav Pech, Paolo Privitera, Petr Schovanek, Francesco Salamida, Radomir Smida, Stan Thomas, Akimichi Taketa, Kenta Terauchi, Petr Travnicek, Martin Vacula

(FAST Collaboration)

Seminar in KIT Auger group, August 25th, 2022



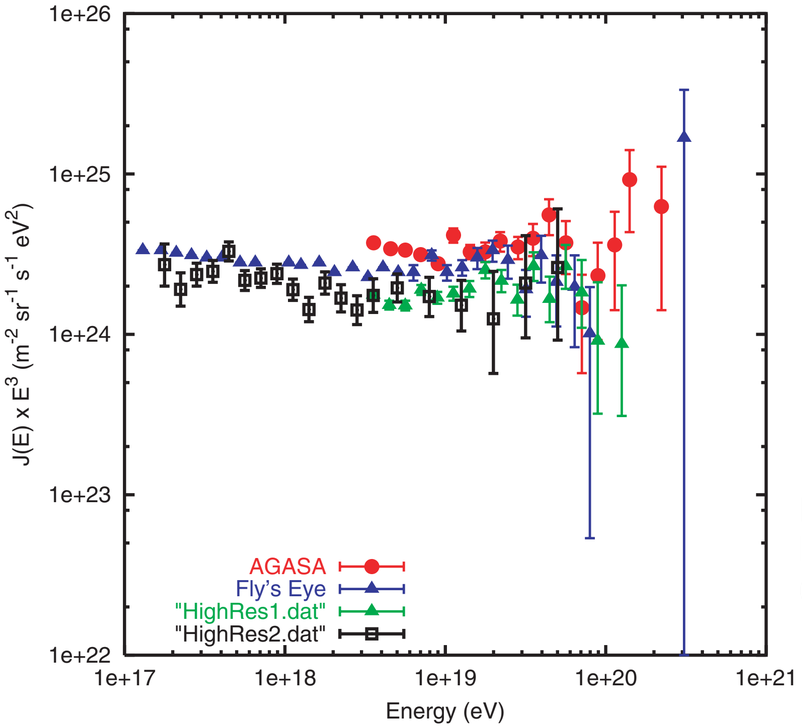
My past visits

2011 Sep.

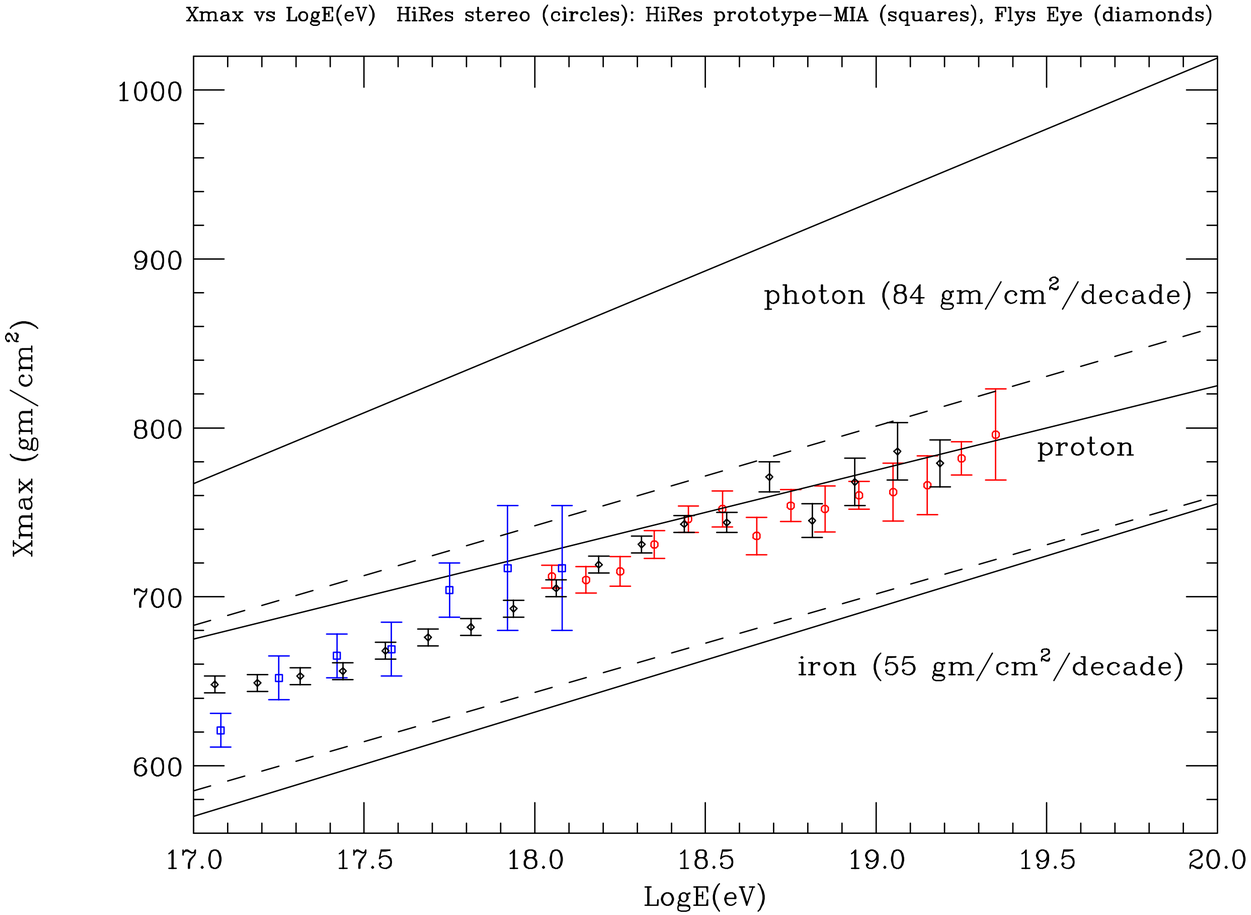
2016 Sep.

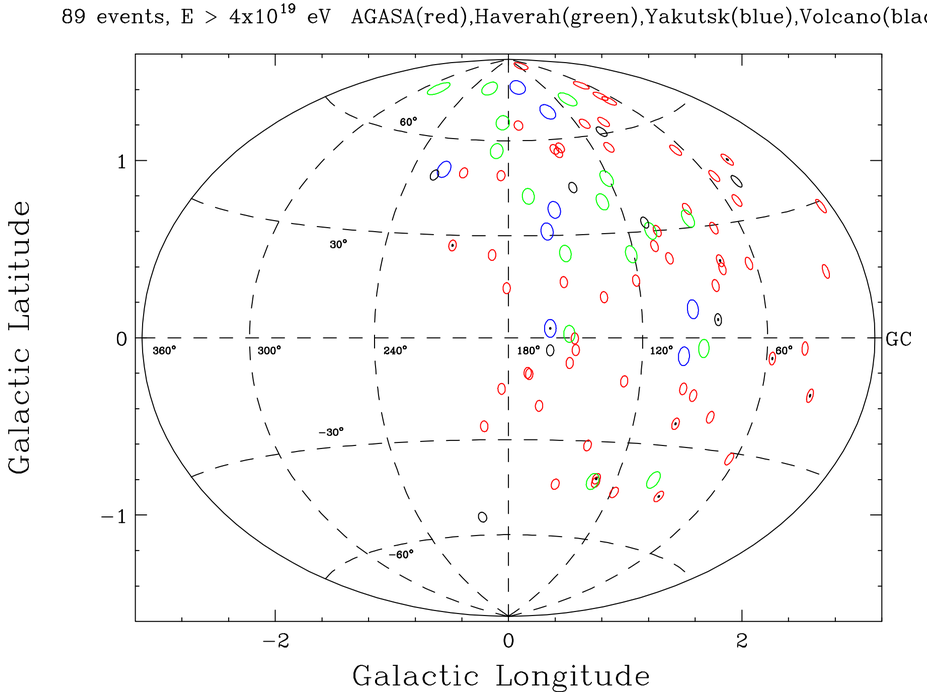
2015 Dec.

~20 years ago...



F W Stecker, J. Phys. G: Nucl. Part. Phys. 29 R47 (2003)



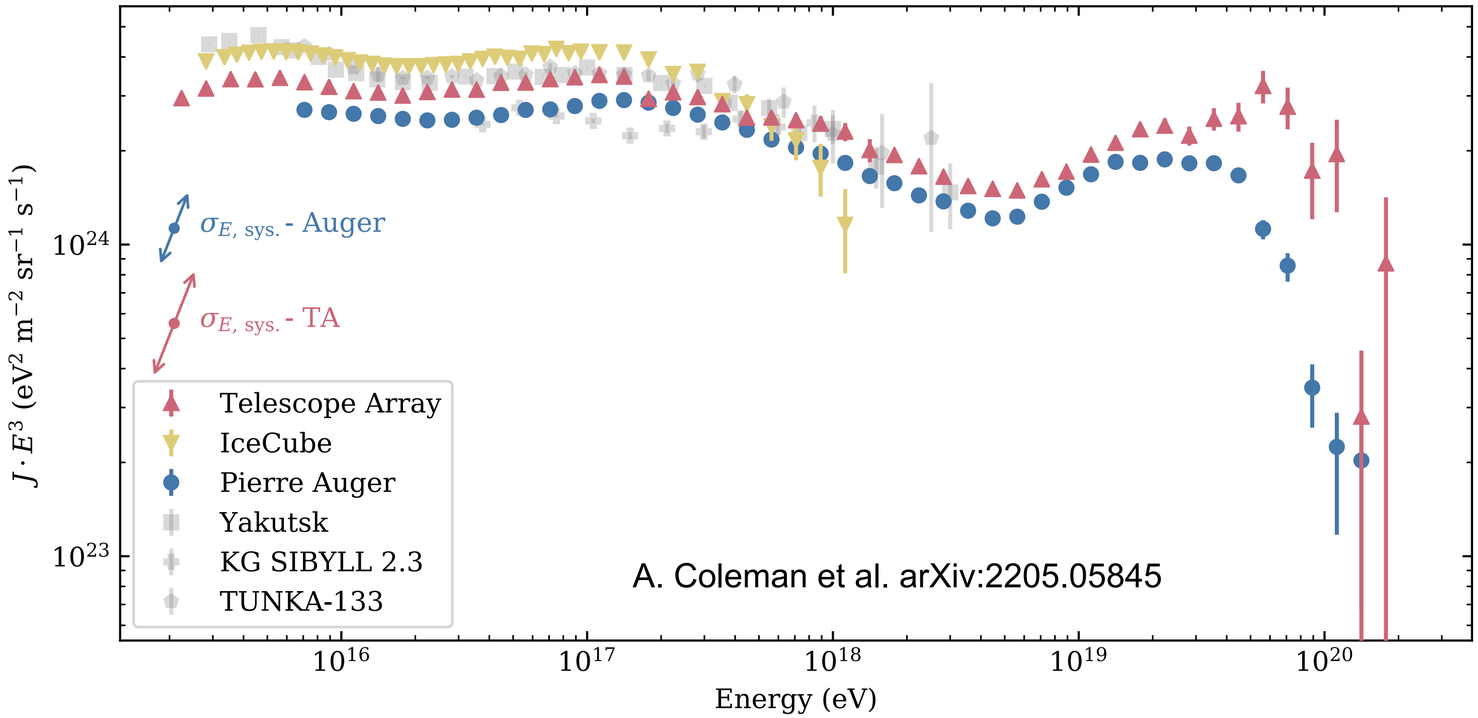


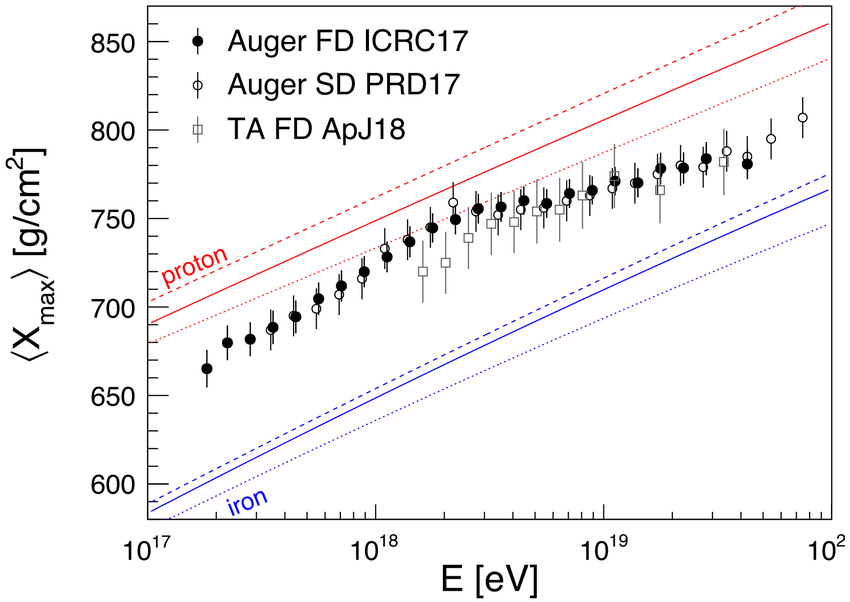
$E > 40$ EeV

J. Cronin, Nucl.Phys.Proc.Suppl. 138:465 (2005)

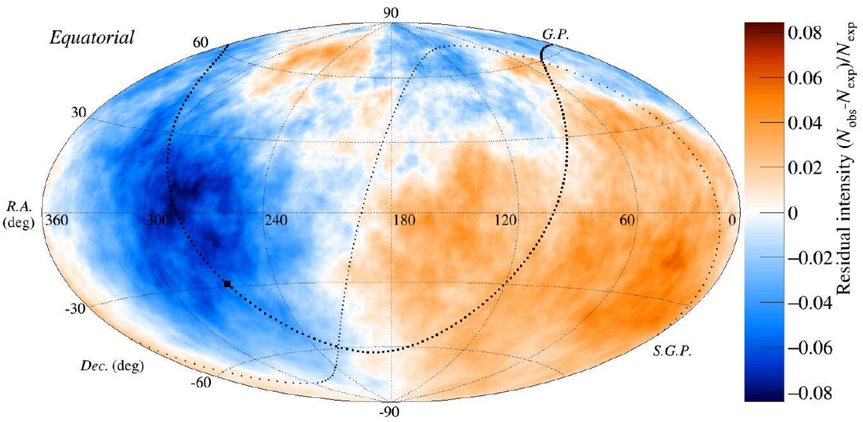
Recent results

R.A. Batista et al., Front.Astron.Space Sci. 6 (2019) 23

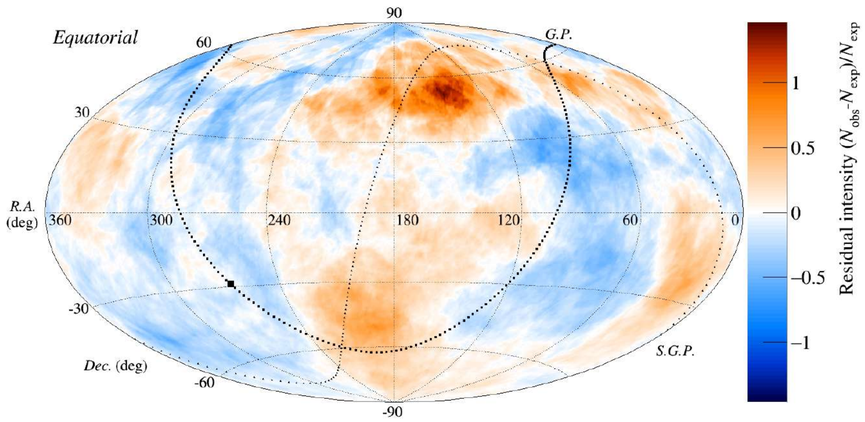


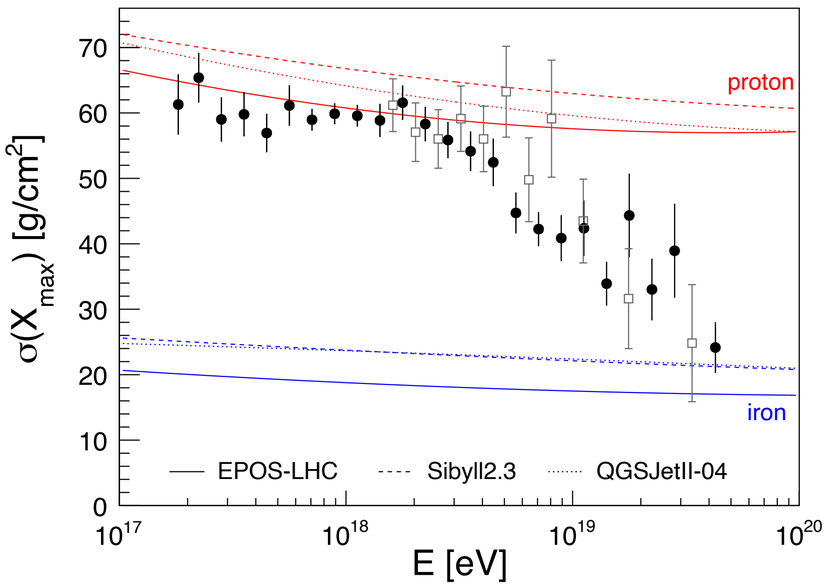


Ankle ($E \sim 10$ EeV)



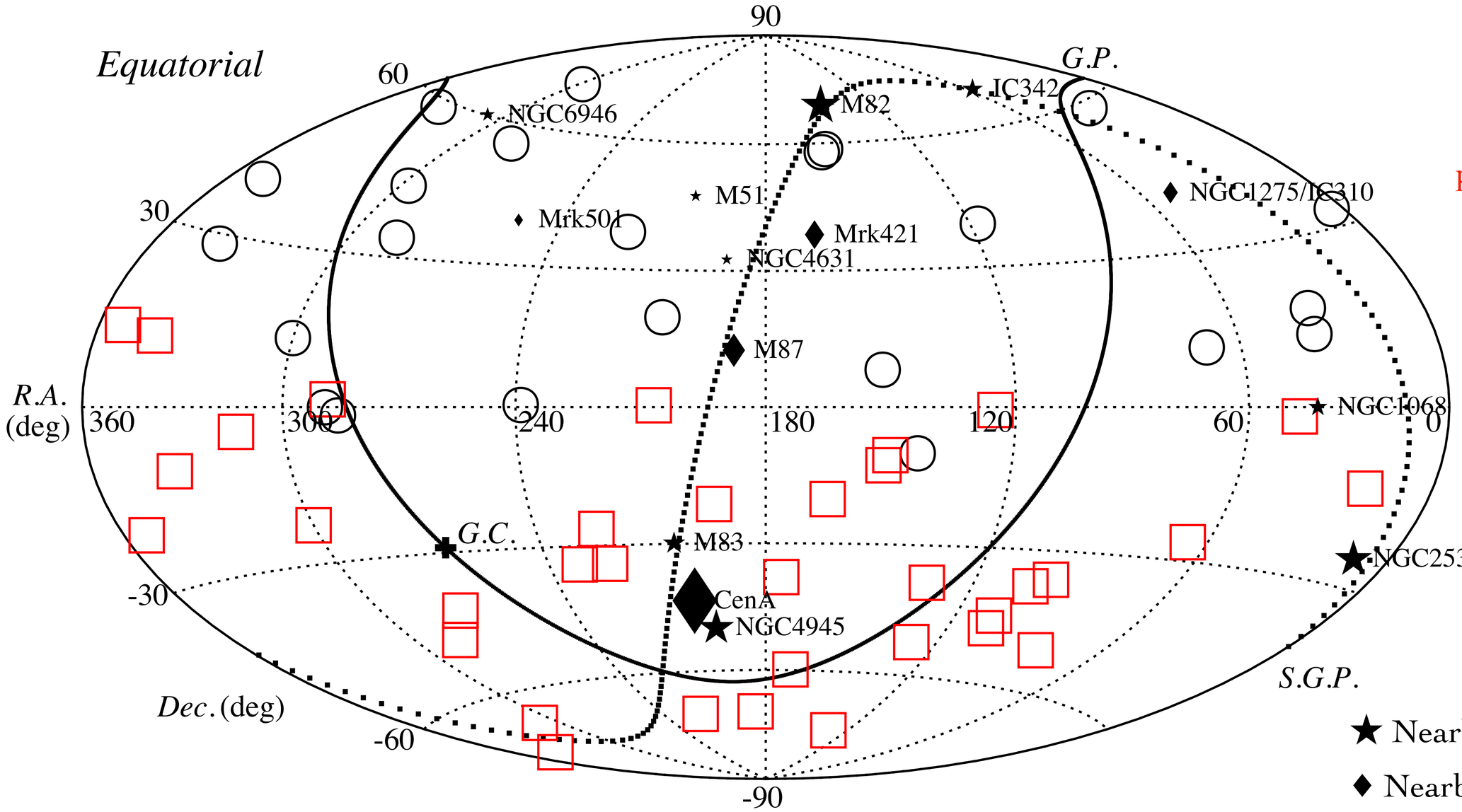
Cutoff ($E \sim 50$ EeV)





T. Fujii et al., PoS (ICRC2021) 402

Beyond GZK energies (>100 EeV)



TA 11 years,
Auger 17 years
arXiv:2206.13492
accepted for
publication in ApJS

★ Nearby star-burst galaxies

♦ Nearby AGNs

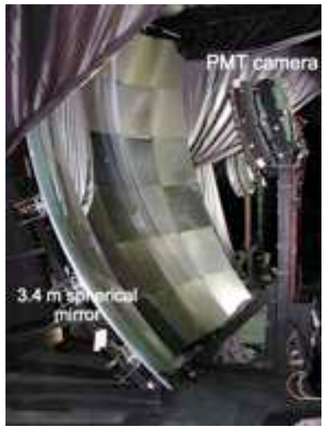
Need more statistics at the highest energies...

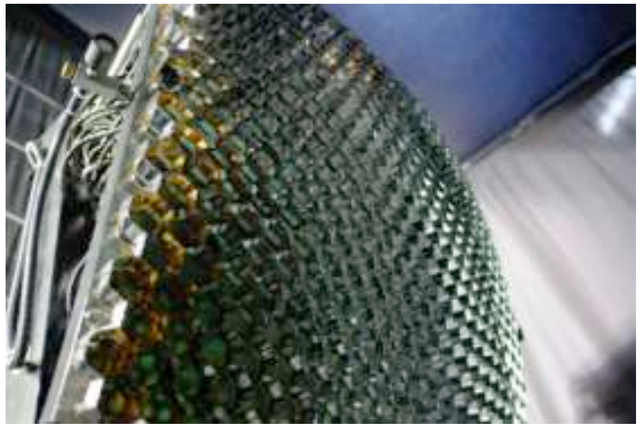
Fluorescence detector Array of Single-pixel Telescopes

EAST
Fluorescence detector Array of Single-pixel Telescopes

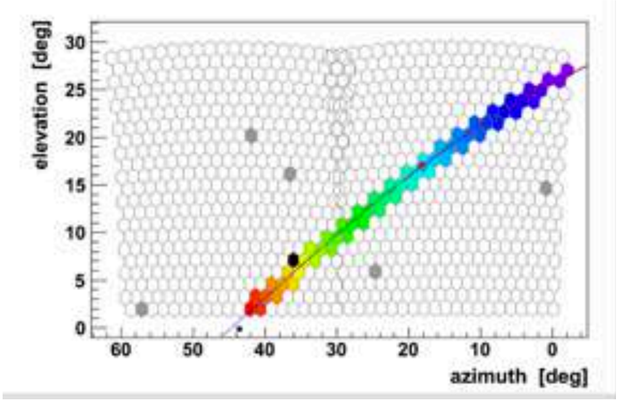
- Target : > $10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma rays
- Huge target volume ⇒ Fluorescence detector array

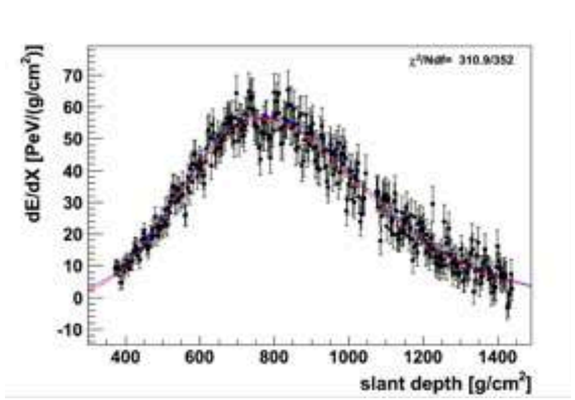
Fine pixelated camera



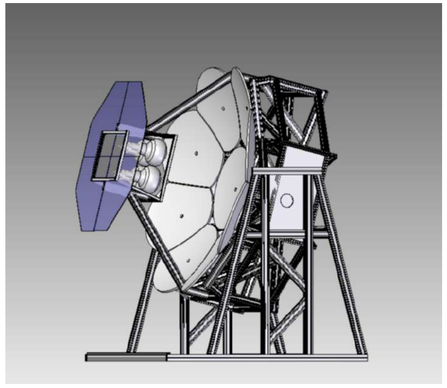


Too expensive to cover a huge area

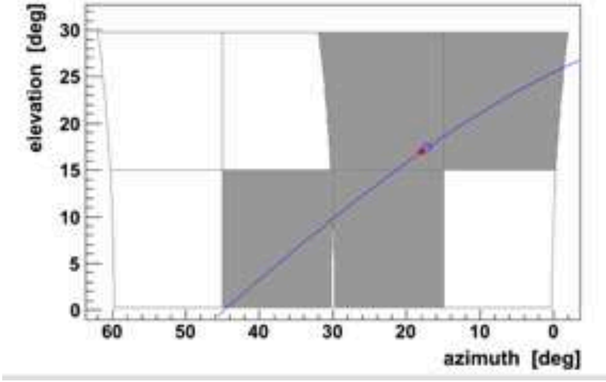


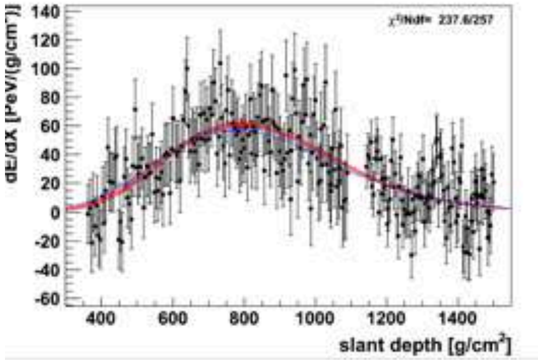


Smaller optics and single or few pixels



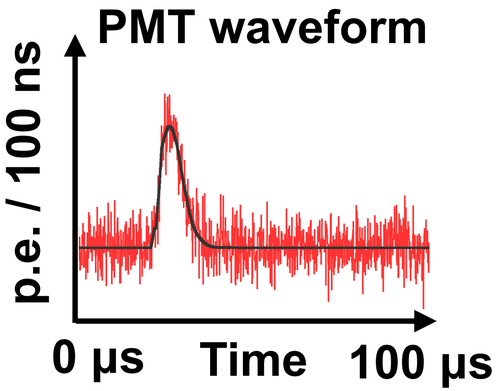
Low-cost and simplified telescope

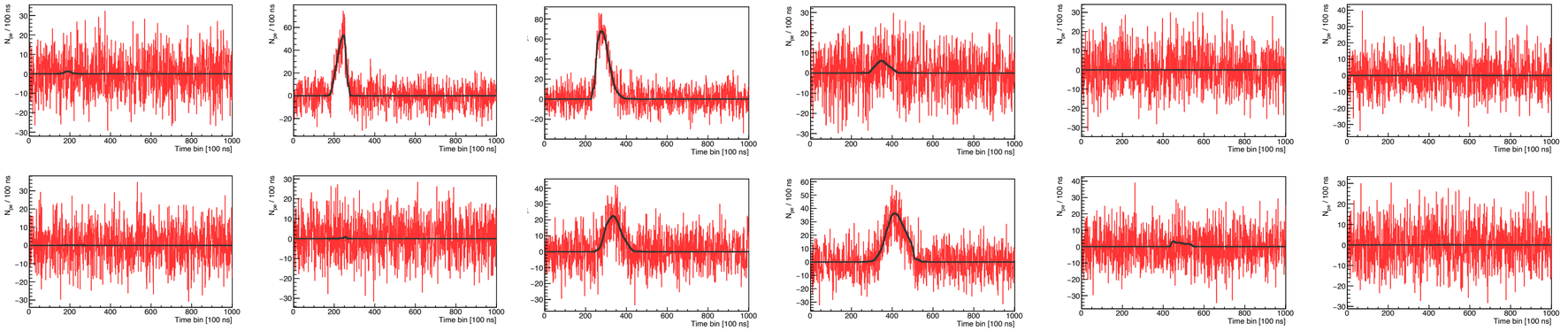


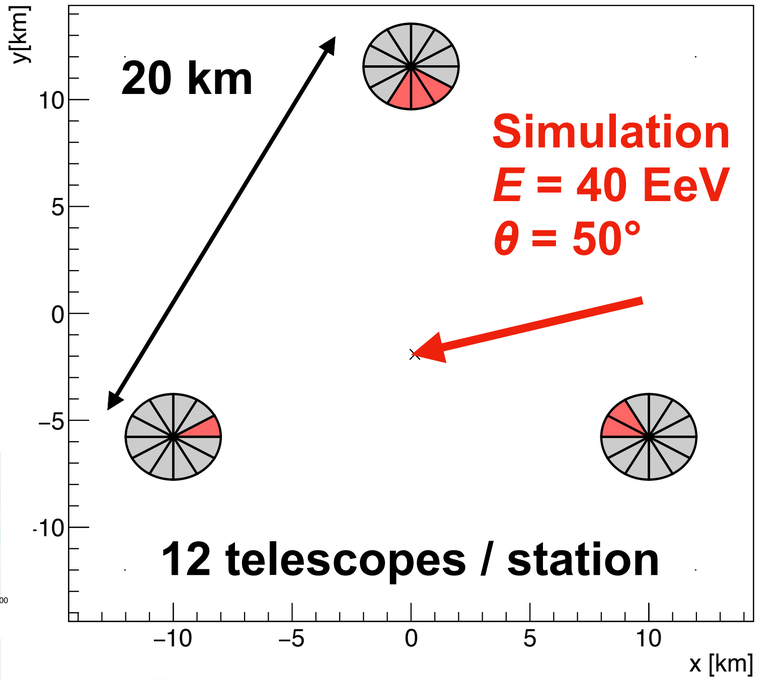


FAST Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

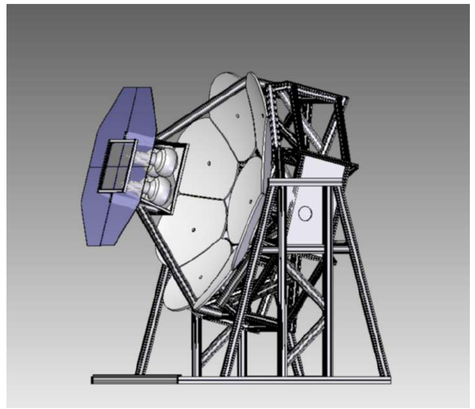






500 stations

→ **150,000 km²**



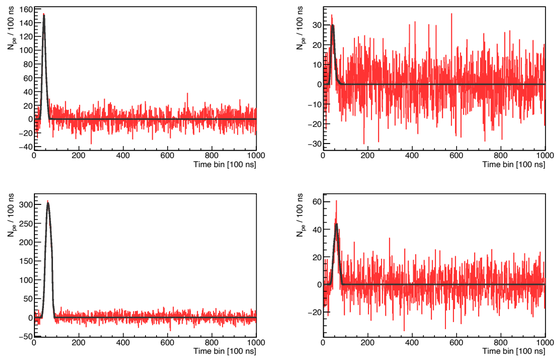
FAST telescope

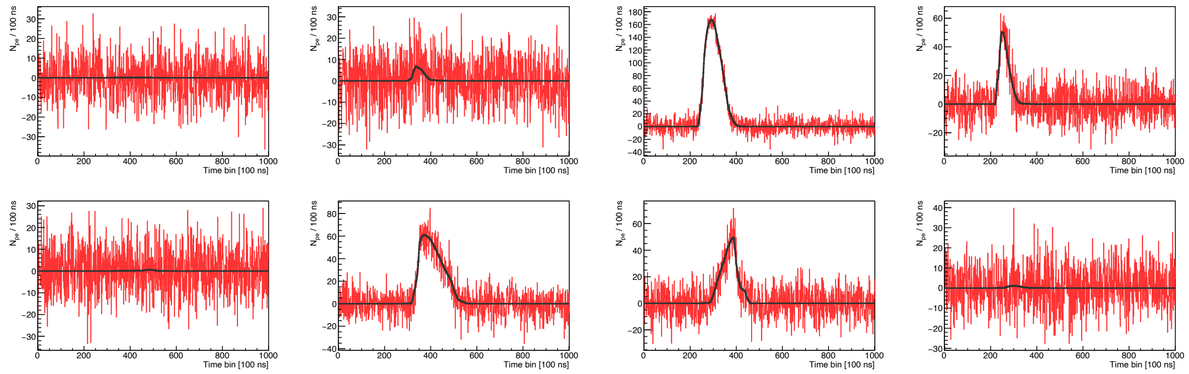
4 PMTs (20 cm diameter)

1 m² aperture (UV filter)

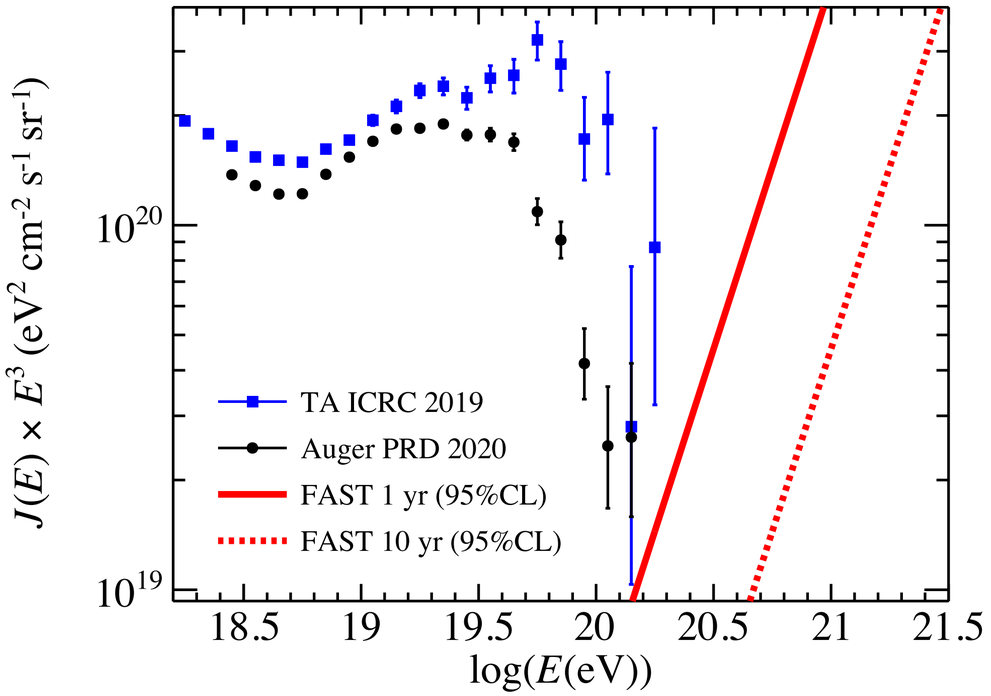
Segmented mirror

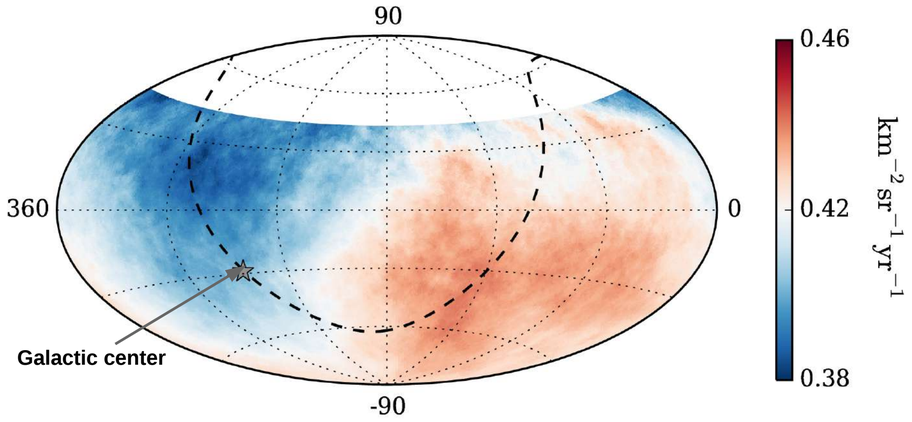
in 1.6 m diameter





Scientific goals for FAST





Pierre Auger Collab. Science 357, 1266 (2017)

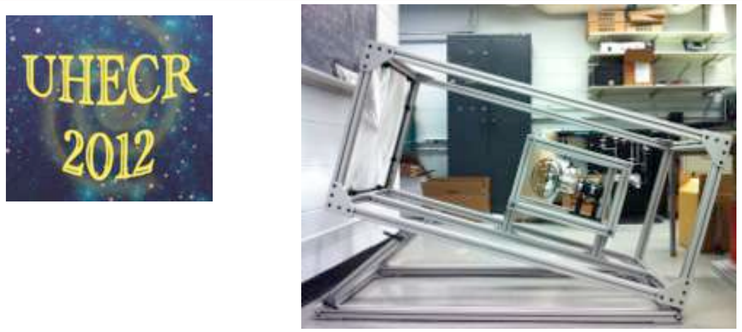
- **To clarify origins and natures of UHECRs**
- **Directional anisotropy on spectrum and composition** with 10× Auger exposure
- **Pros**
  - Calorimetric energy determination
  - Mass-composition sensitivity using $X_{\max}$
  - Less dependent on hadronic interaction models
- **Cons**
  - Low duty cycle, 10 - 20%
  - May calibration components(PMT gains, Optics, atmospheric parameters, telescope direction)
  - Understanding directional exposure
    - Now we have a dipole structure anisotropy as a calibration source
- **Stand-alone operation required**

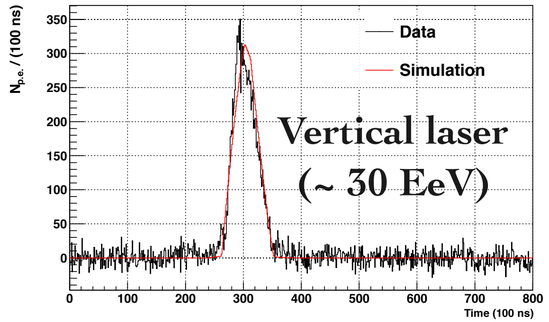
Validations of the FAST concept

Feb. 2012

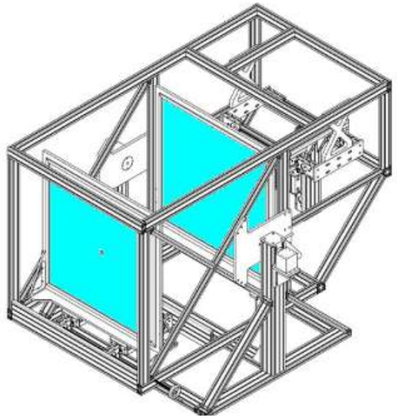
A conceptual design for a large ground array of Fluorescence Detectors

P. Privitera in UHECR 2012

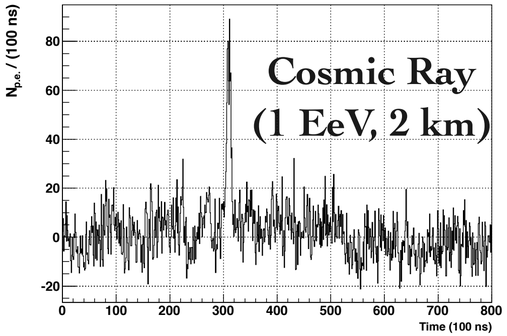




Apr. 2014



EUSO-TA optics
+
Single-pixel camera



T. Fujii et al., Astroparticle Physics *74* (2016) 64-72

Oct. 2016

Sep. 2017

Oct. 2018

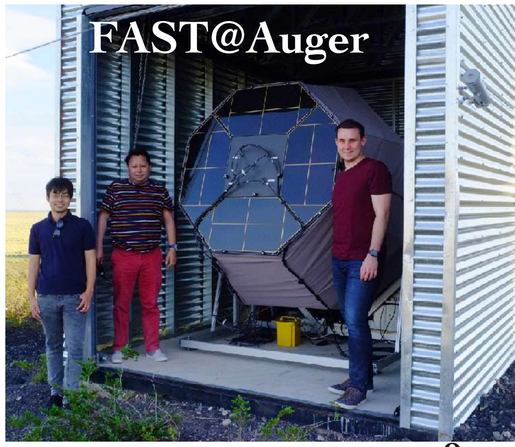
@TA

Apr. 2019

Jun. 2022

@Auger

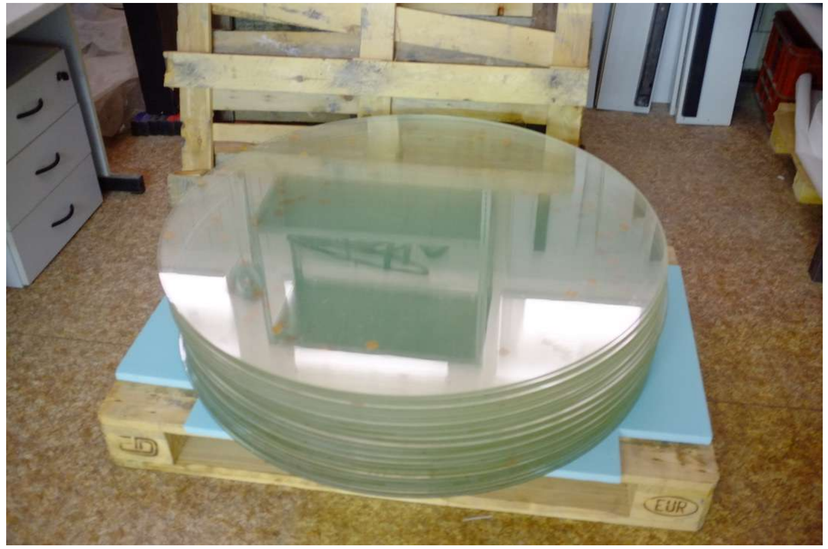
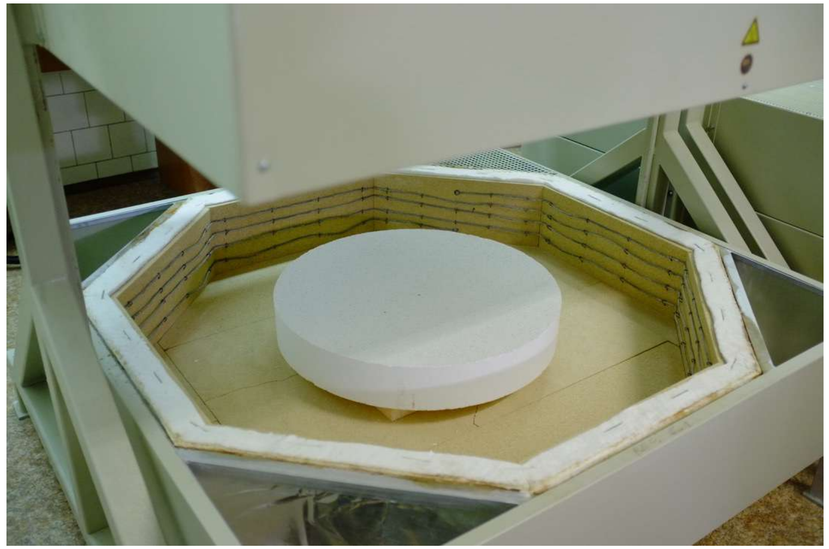
D. Mandat et al., JINST 12, T07001 (2017)



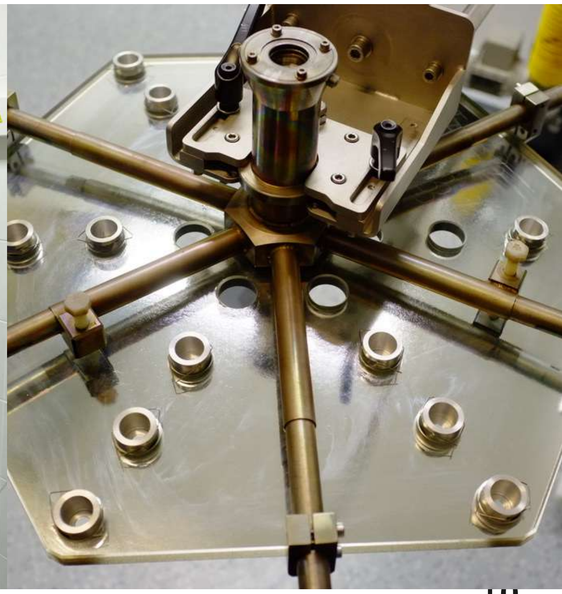
M. Malacari et al., Astroparticle Physics 119 (2020) 102430

EAST
Fluorescence detector Array of Single-pixel Telescopes

Mirror production at Olomouc, Czech republic

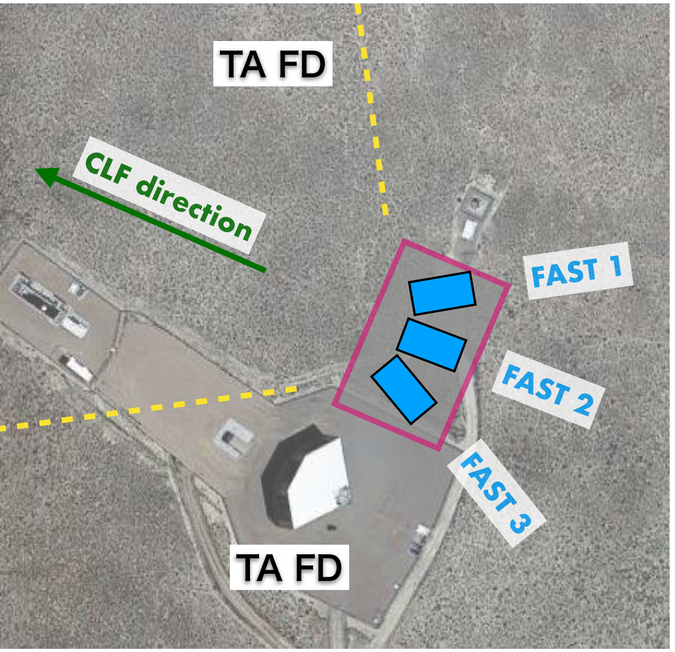


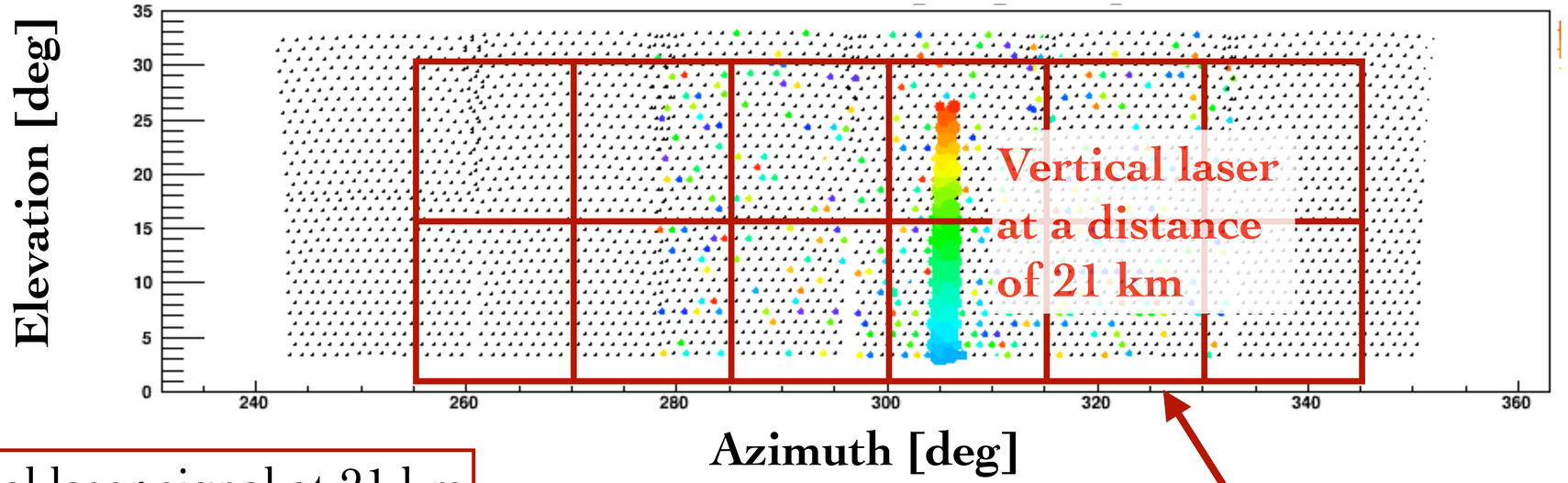
Installation of the FAST prototype

FAST observation at TA site

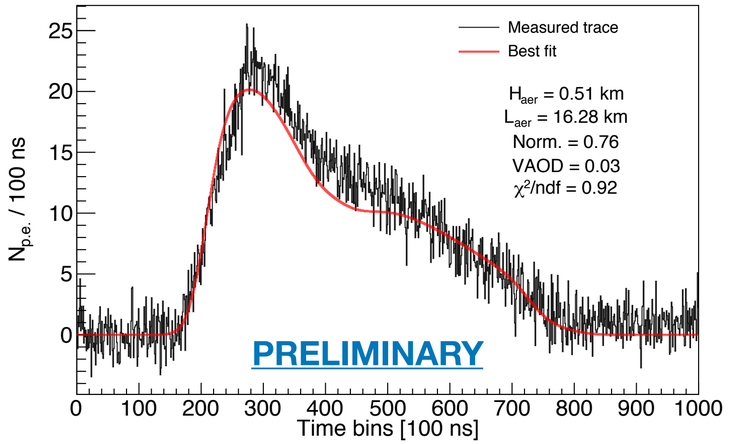
- Remote controlling observation
- Synchronized operation with external triggers from Telescope Array fluorescence detector (TA FD)
- 80% FoV of TA FD



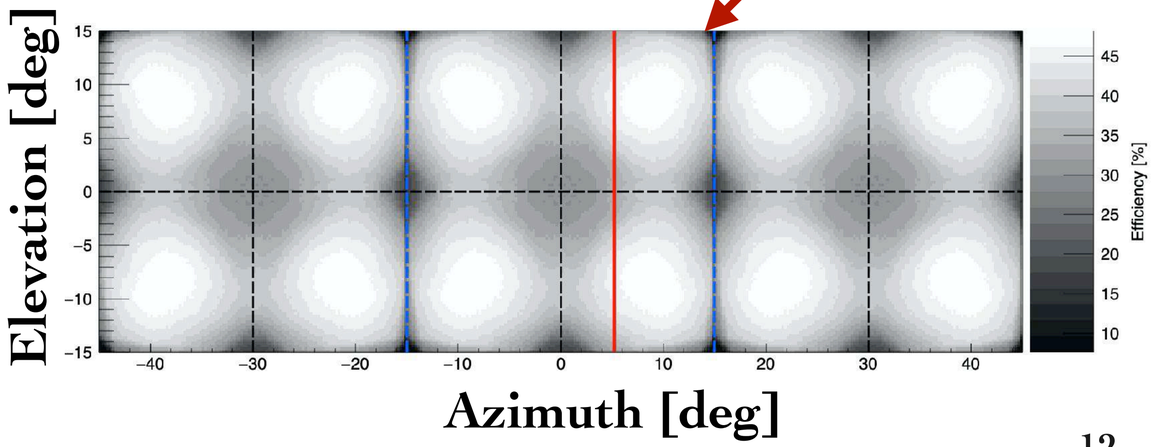
TA FD FoV (12 telescopes, 33°×108°)



Vertical laser signal at 21 km (280 shot average)

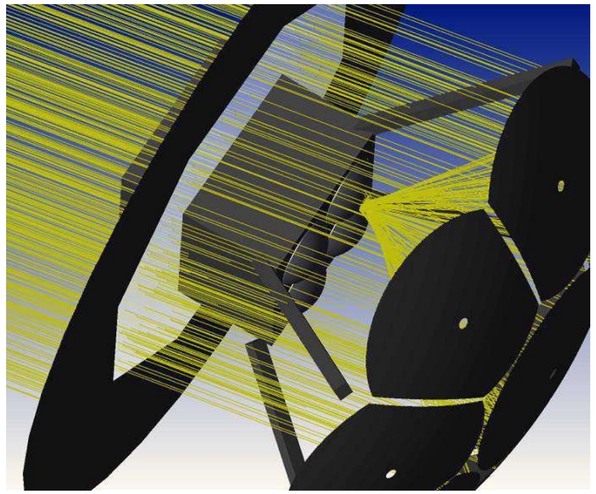


FAST FoV (3 telescopes, 30°×90°)



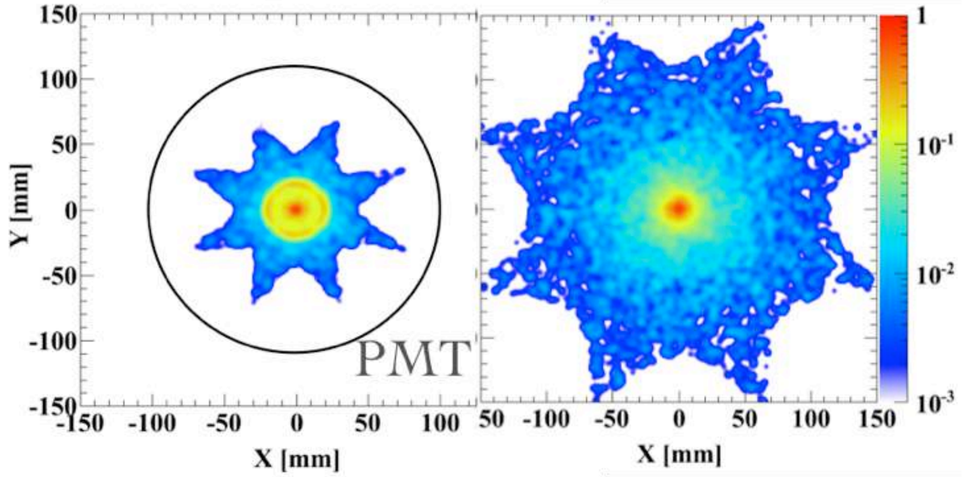
Data/simulation comparison using a distant vertical laser

FAST
Fluorescence detector Array of Single-pixel Telescopes

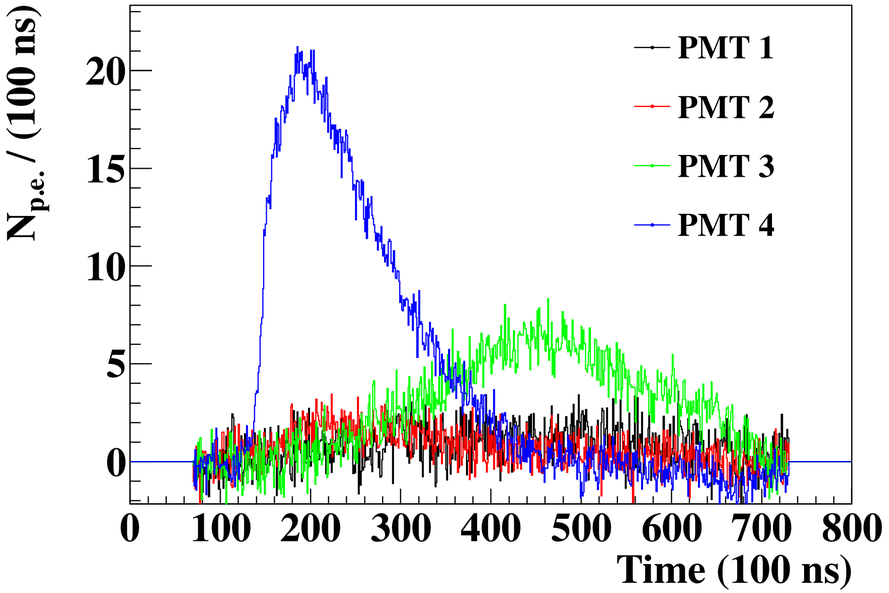


Spot-size

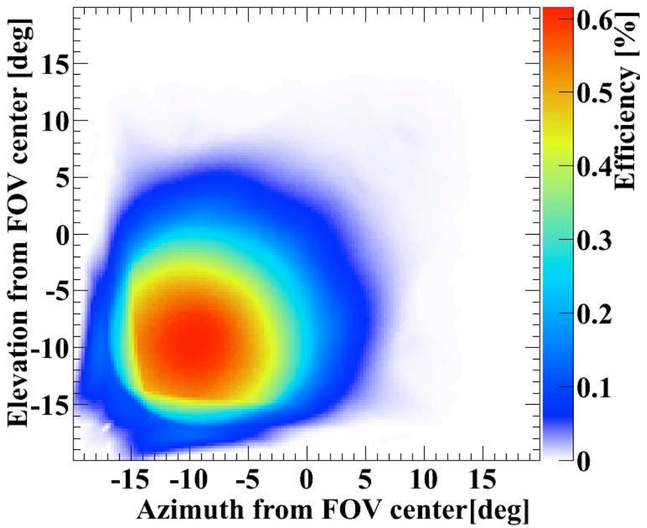
focal plane 50 mm offset



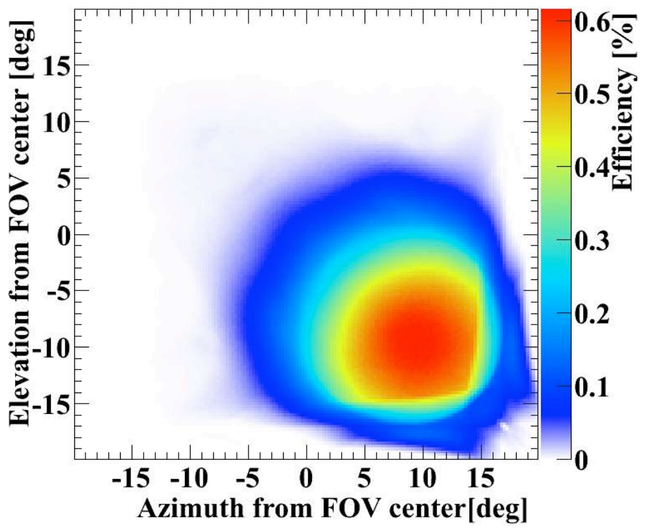
A UV vertical laser at 21 km away

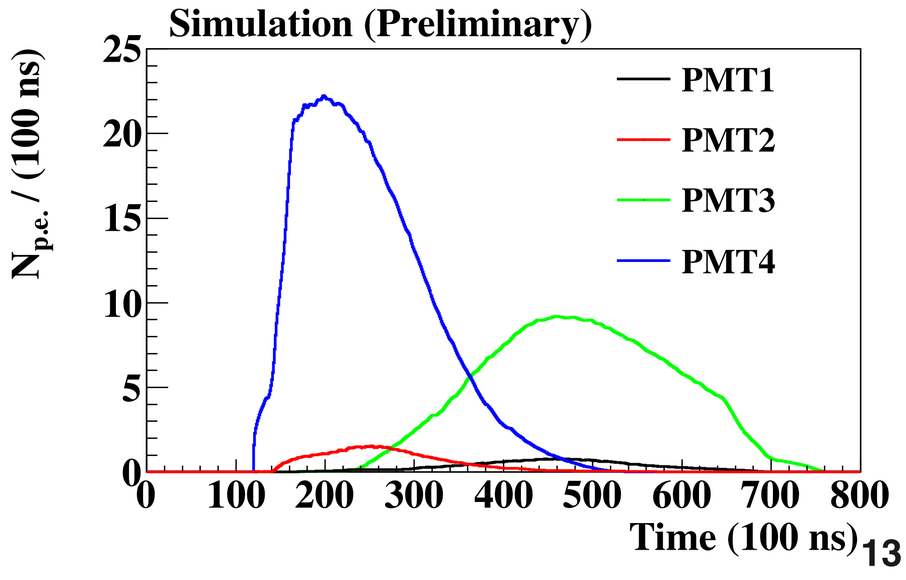


Directional characteristic (PMT2)



(PMT 4)

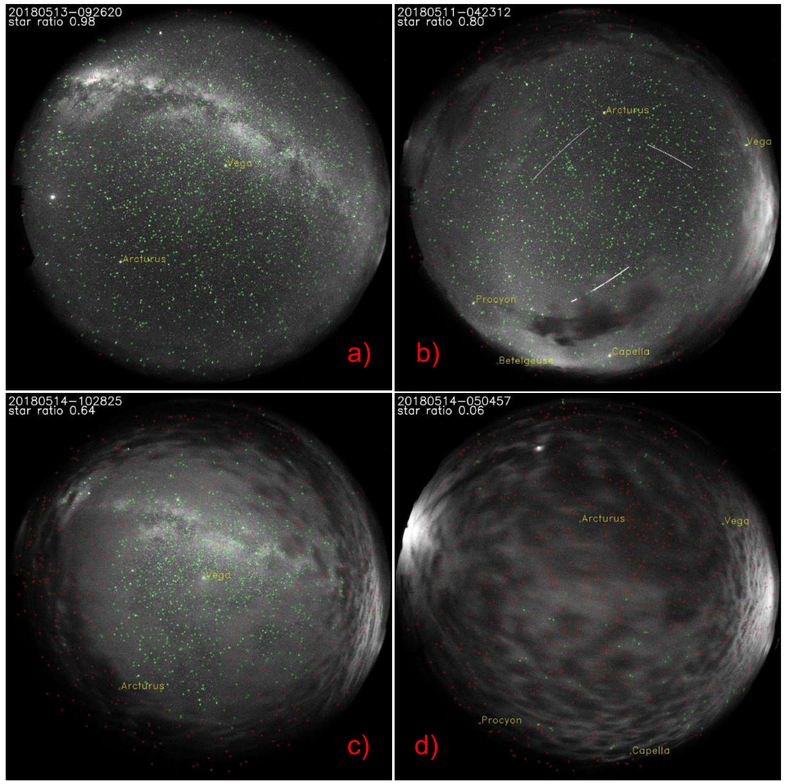




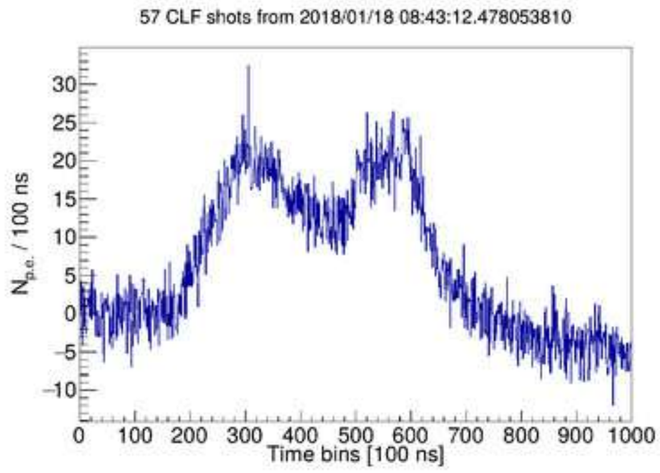
Atmospheric monitoring studies

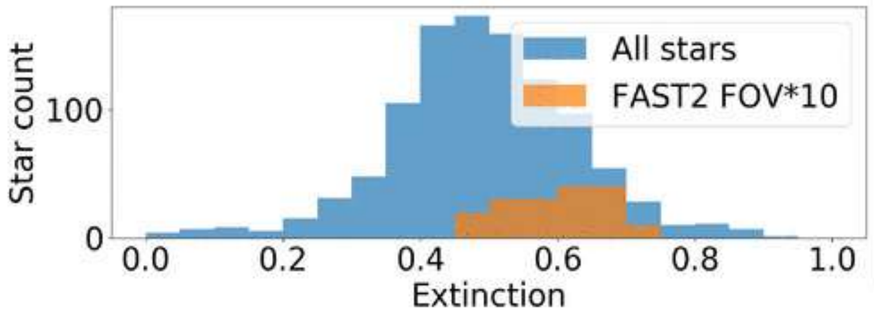
L. Chytka et al. (FAST Collaboration), JINST 15 T10009 (2020)

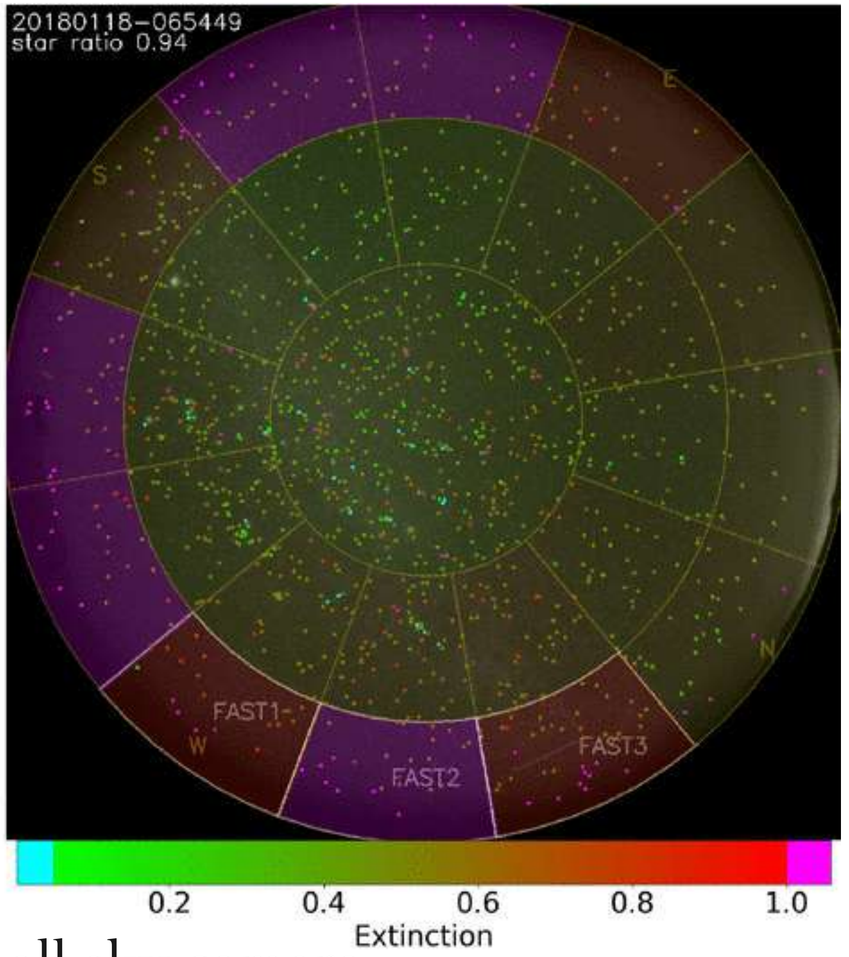
Automated all-sky camera



A distant laser detected with FAST





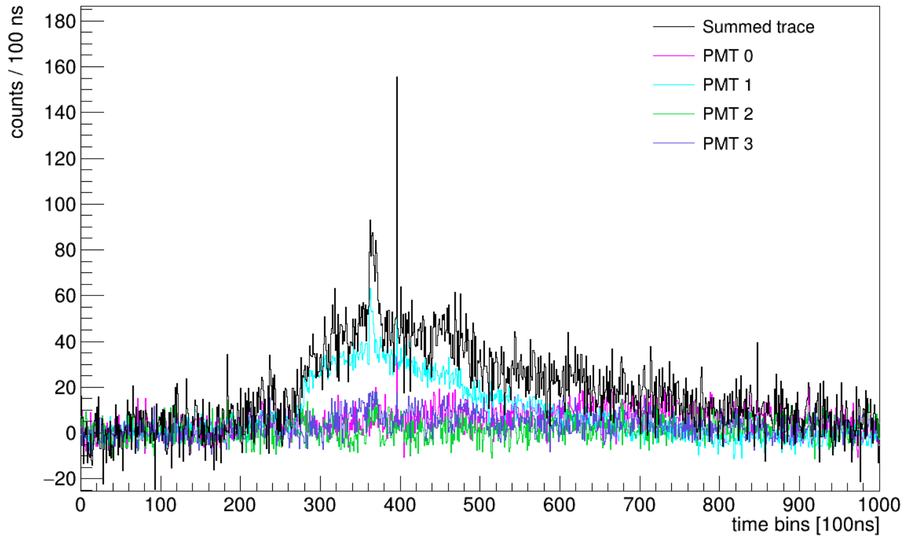


Star extinctions measured with all sky camera

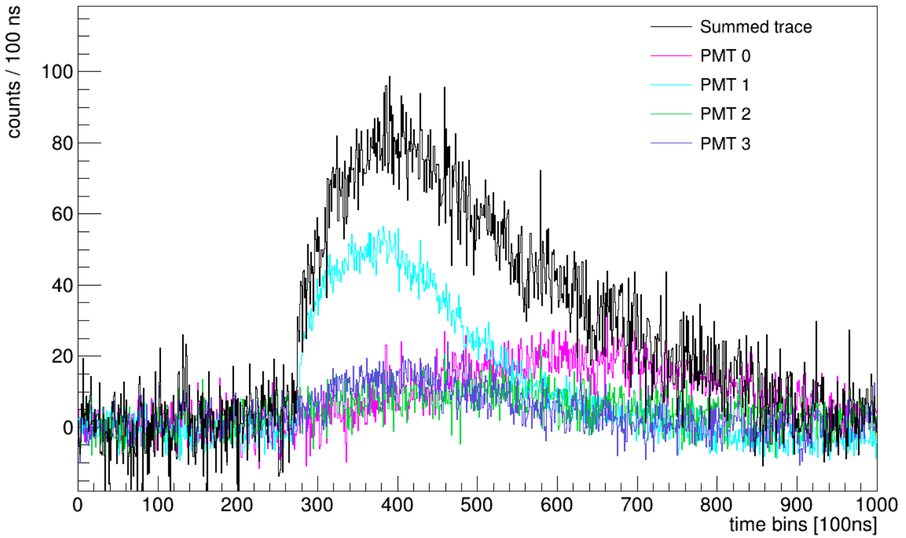
CLF signal (26 km) by FAST@Auger

Fluorescence detector Array of Single-pixel Telescopes

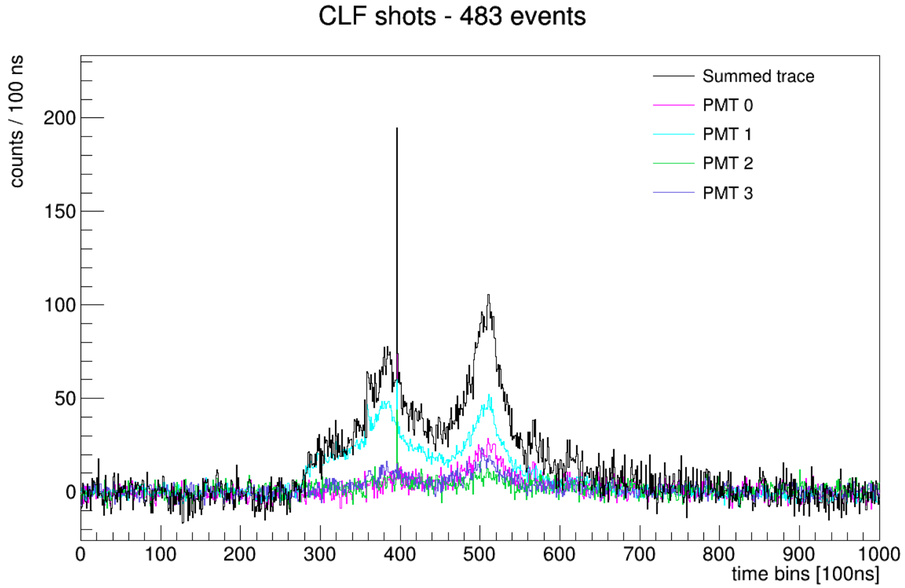
July 3rd



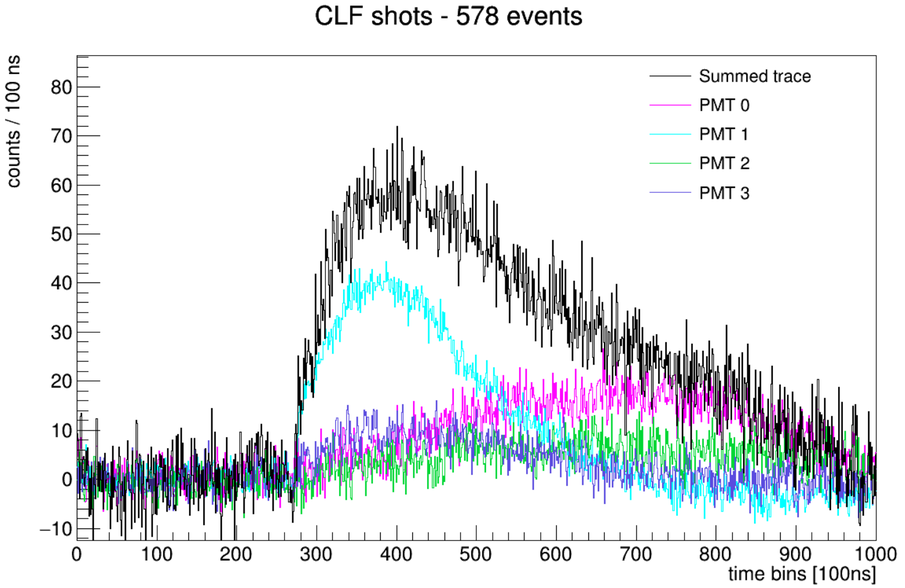
July 4th



July 5th

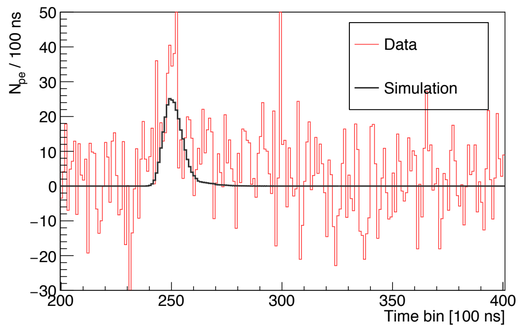


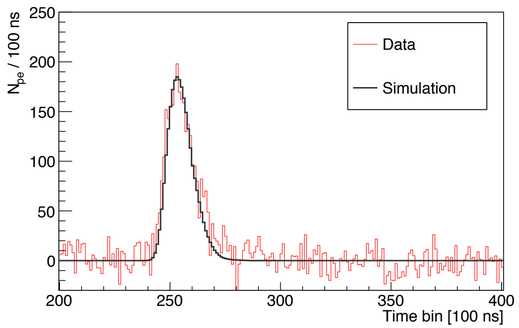
July 6th

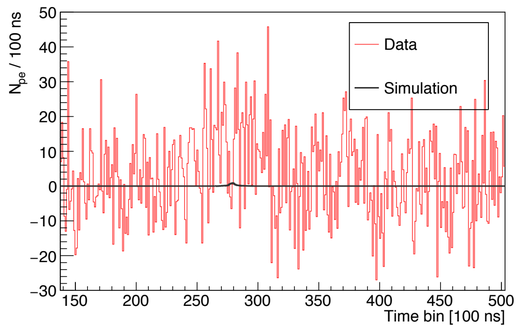


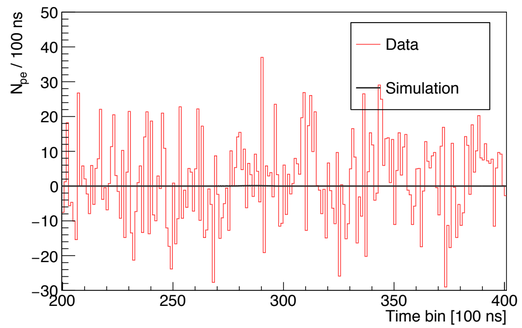
Cherenkov dominated event with "top-down" reconstruction

FAST Fluorescence detector Array of Single-pixel Telescopes



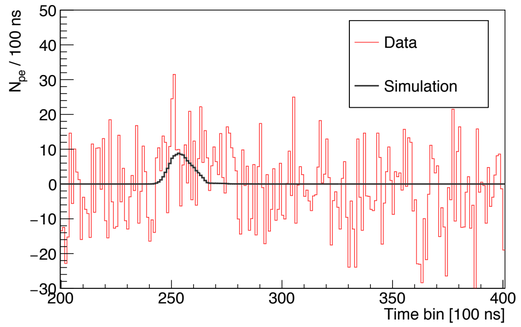


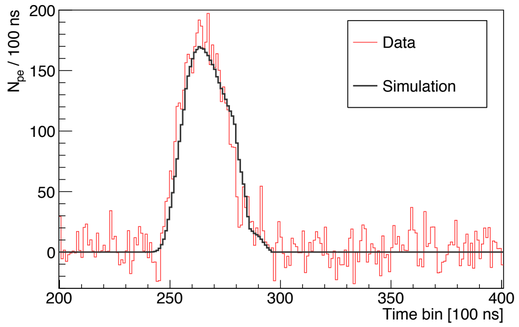


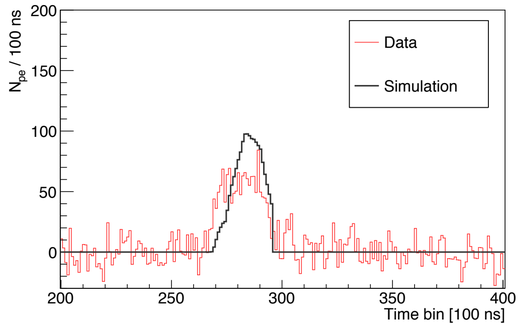


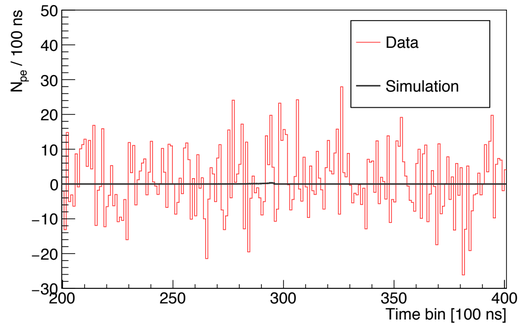
FAST Fluorescence detector Array of Single-pixel Telescopes

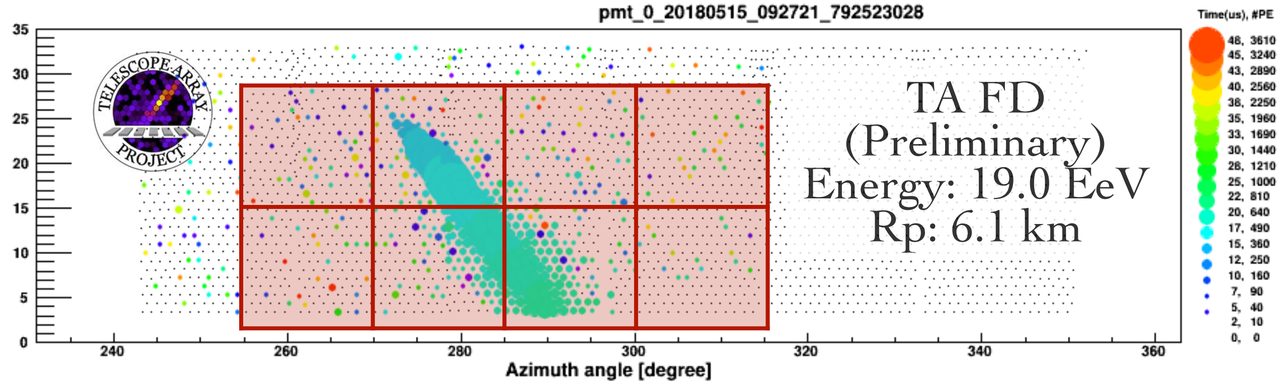
FAST waveforms + Expected signals from top-down reconstruction (Data, Simulation by the best-fit parameters)









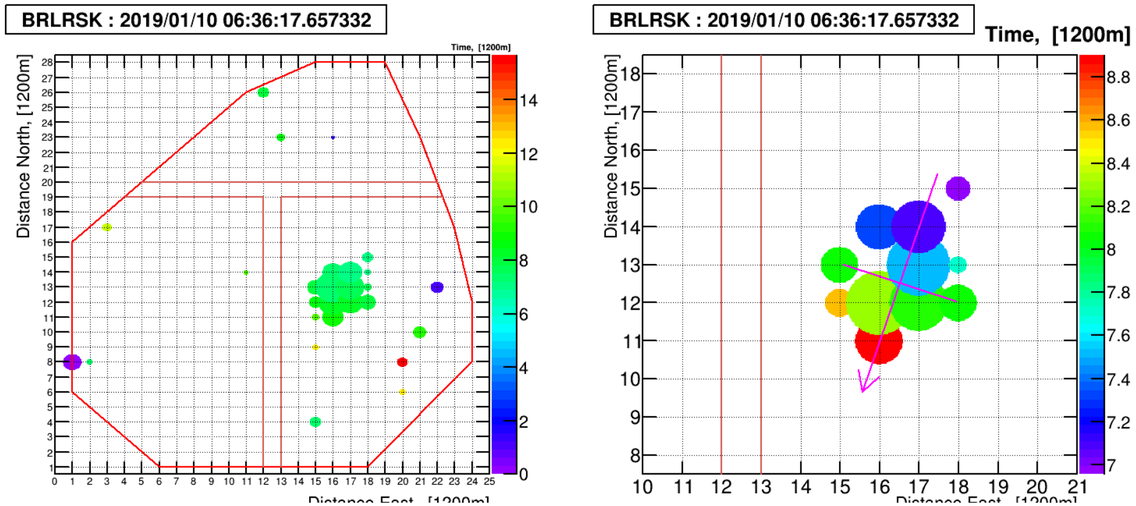


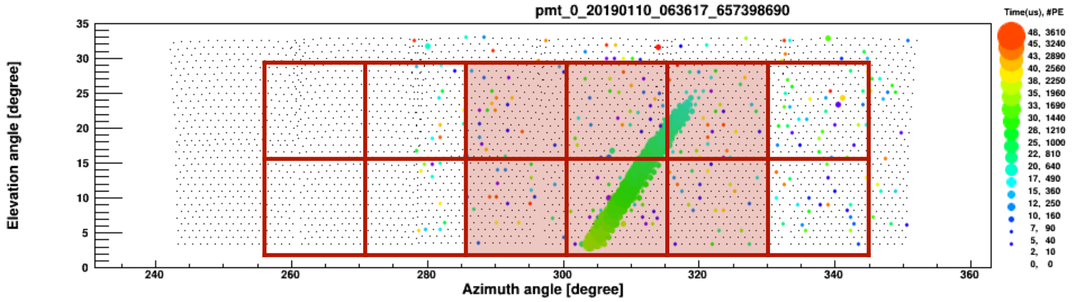
FAST top-down reconstruction (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-96.7 deg	7.9 km	-9.0 km	842 g/cm^2	17.3 EeV

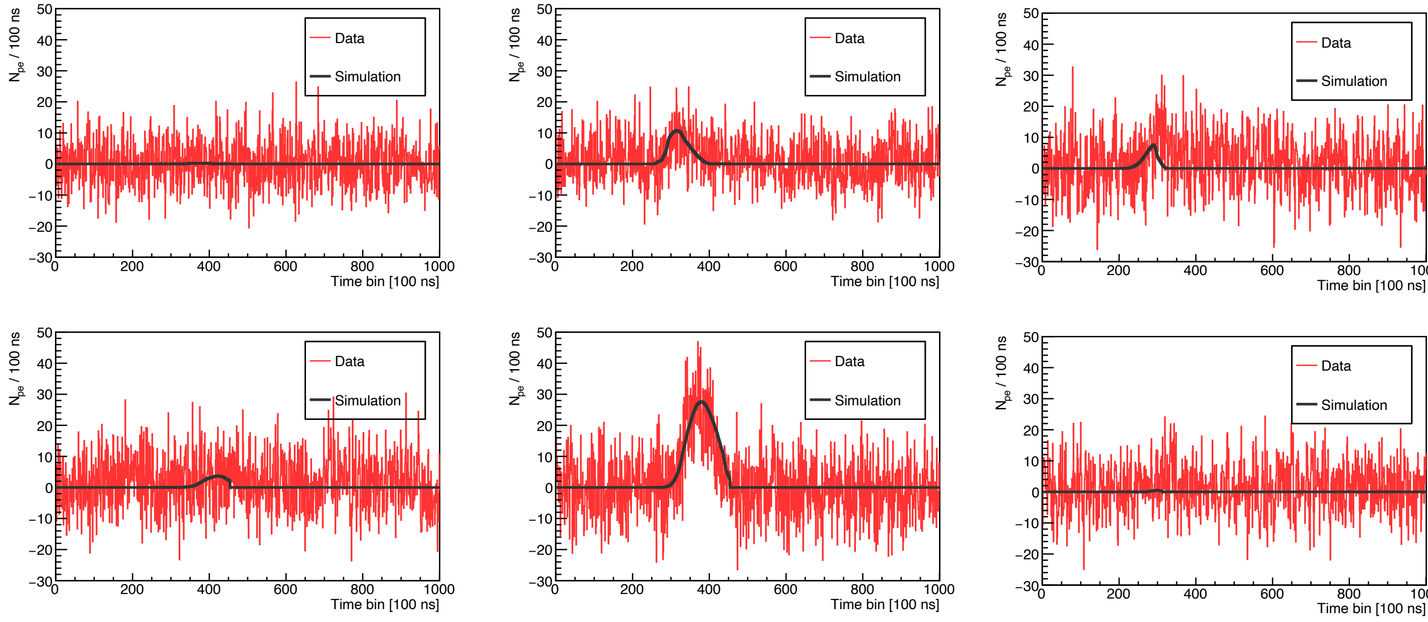
Fluorescence dominated event

TA result





FAST result



TA SD (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Energy
36.2 deg	18.0 deg	5.0 km	-4.5 km	15.8 EeV

TA FD (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Energy
33.2 deg	35.8 deg	6.1 km	-5.3 km	20.0 EeV

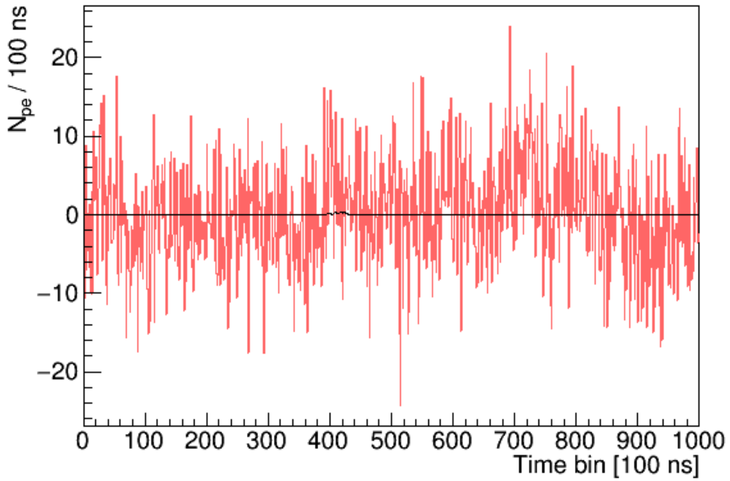
FAST top-down reconstruction (Preliminary)

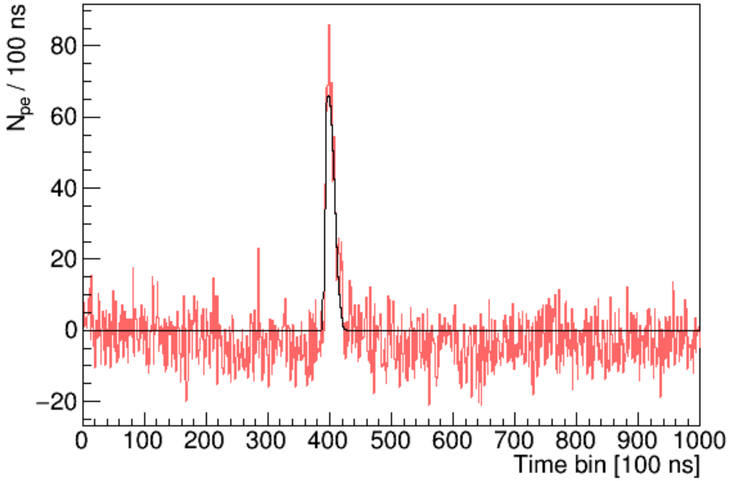
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
33.9 deg	19.3 deg	4.6 km	-4.7 km	808 g/cm^2	18.8 EeV

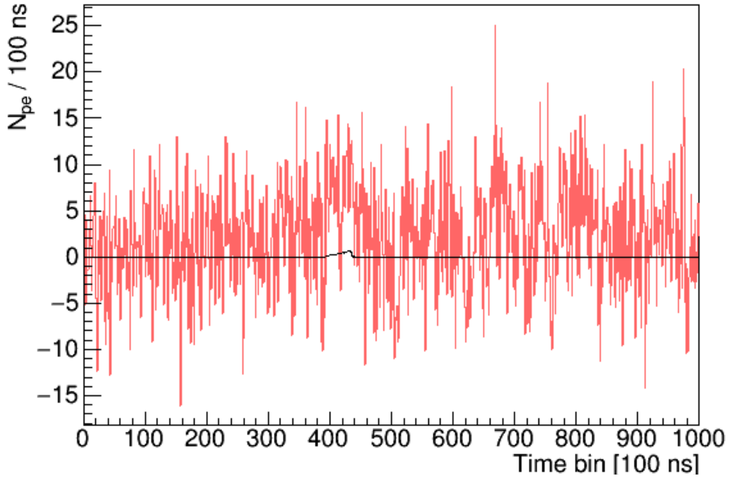
FAST@Auger and Los Leones coincidences

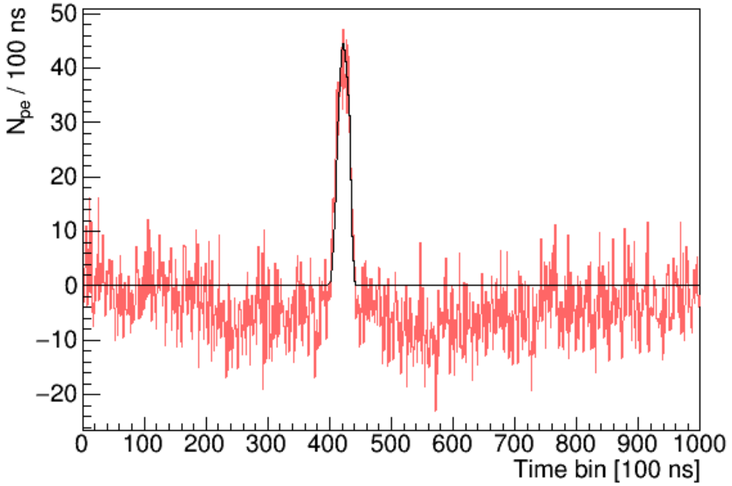
Work: Petr Hamal, Jose Bellido, Justin Albury

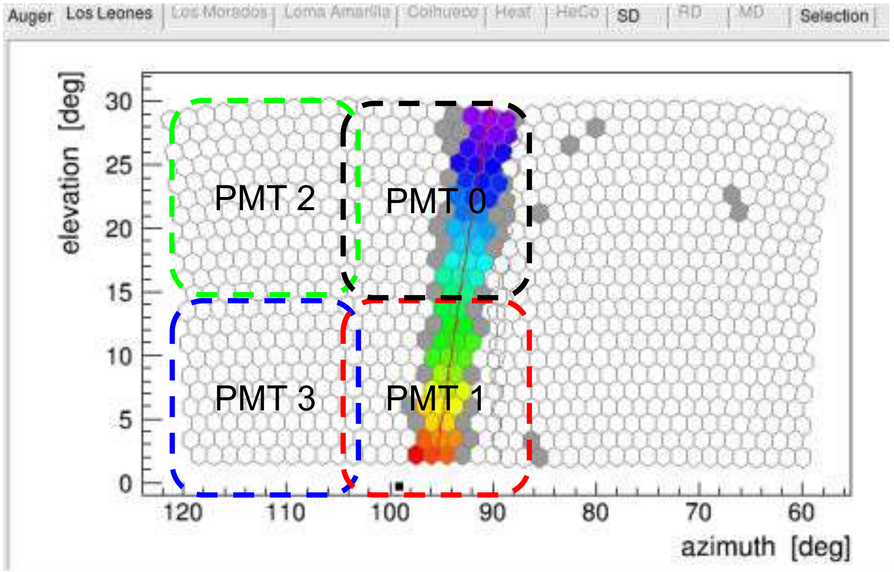
Fluorescence detector Array of Single-pixel Telescopes











Event Info | Pixels

run 7766, event 391

time stamp: 1266895981 s 703698071 ns

Trigger: 'Physics - Int or L/R trigger', 'Shower Candidate'

in Los Leones mirror 3 4 (in DAQ: 1 2 3 4 5 6)

geometry: hybrid, station 427 (ToT), showerPlaneDistance = 243 m

(θ, ϕ) = (12.8±0.5, 16.0±2.3) deg

(x, y) = (-16.85±0.01, -24.45±0.02) km

R_p = 3.10 ± 0.02 km

profile: 4-parameter Gaisser-Hillas (type: classic)

$E = (1.74 \pm 0.14) \times 10^{18}$ eV

$X_{max} = 665 \pm 35$ g/cm^2

$(dE/dX)_{max} = 2.58 \pm 0.17$ PeV/(g/cm^2)

$(\lambda, X_0, \text{fwhm}) = (64\pm9, -157\pm111, 542)$ g/cm^2, $f_{asym} = 0.45$

Cherenkov-fraction = 0%, mva=0 deg.

databases:

Mie attenuation: model

LIDAR: no data ; CloudCam: no data; CloudMap: no data

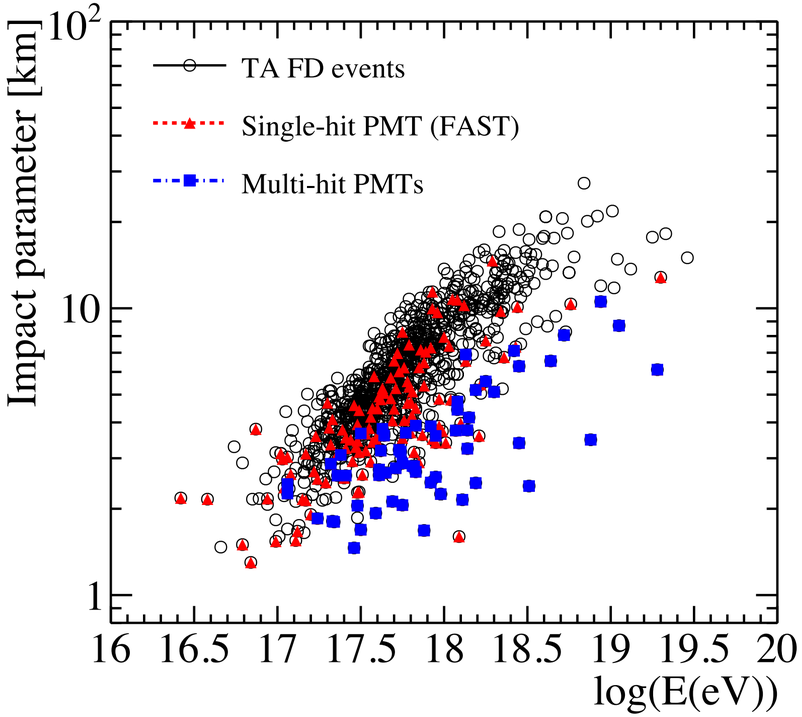
molecular profile: GDAS; time correction: bad

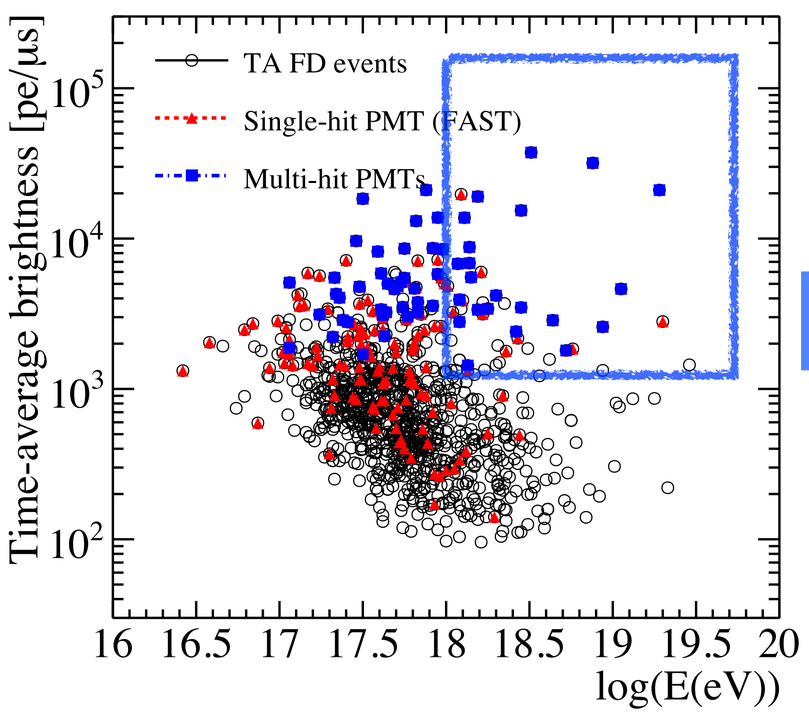
(FAST) 0.965 ± 0.201 EeV, 640 ± 151 g/cm^2

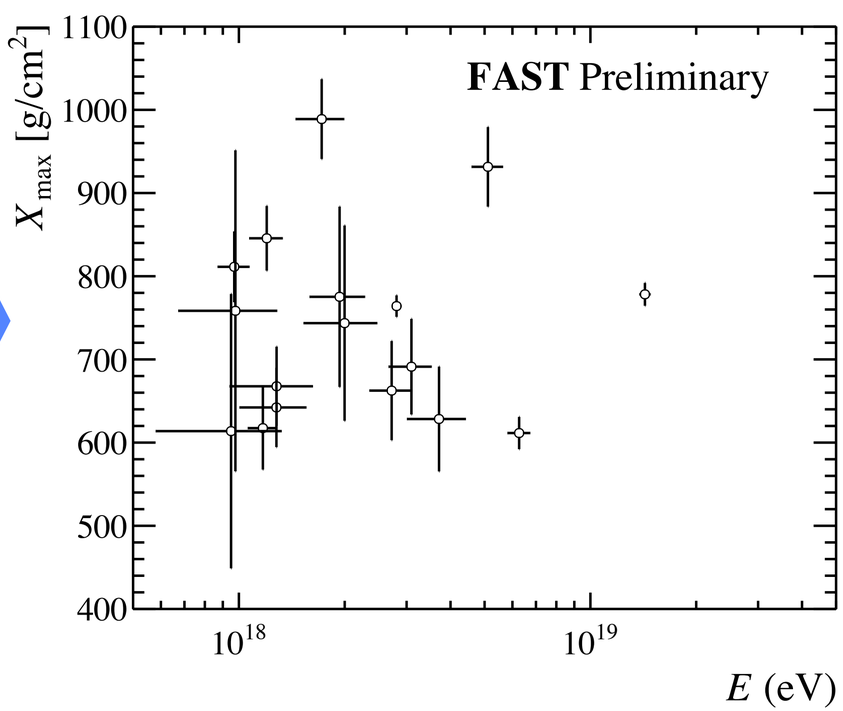
(Auger) 1.74 ± 0.14 EeV 665 ± 35 g/cm^2

Reconstructing UHECRs with FAST@TA

- Data period: 2018/Mar/19 - 2019/Oct/14, 225 hours
- Event number: **964** (TA FD) -> **179** (Single-hit with FAST, S/N > 6σ, Δt > 500 ns) -> **59** (Multi-hit)
  - The shower parameters are reconstructed by TA FD monocular result



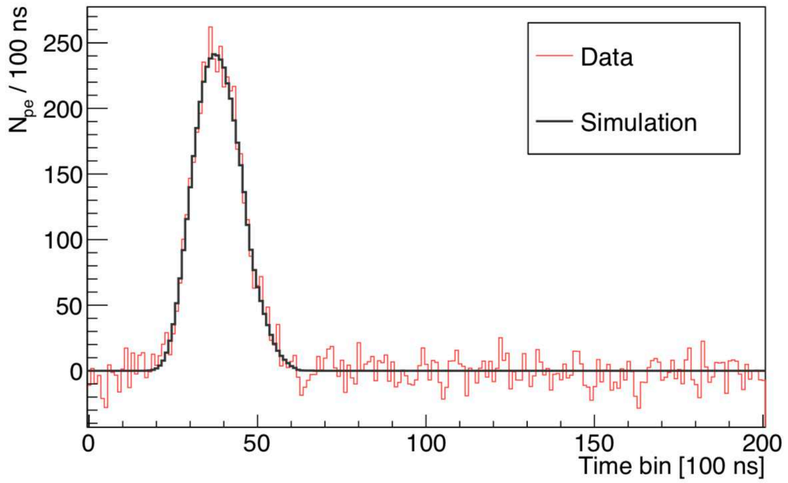




- Use **top-down reconstruction** for **events with multi-hit PMTs above 1 EeV**
  - First-guess geometry given from the TA FD

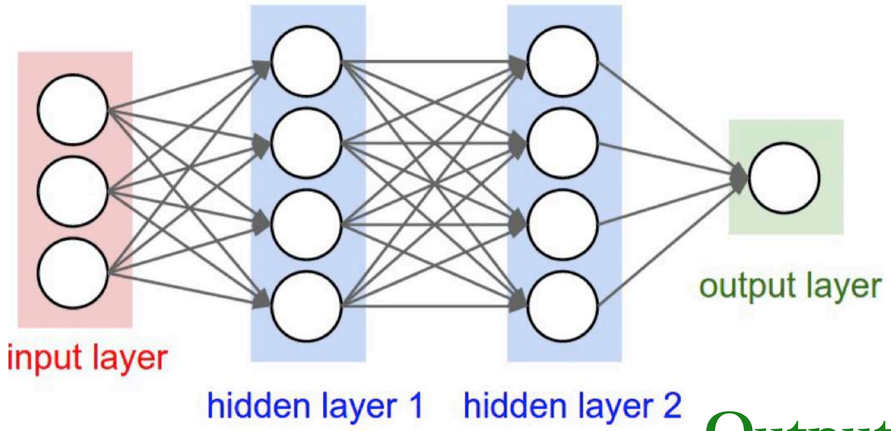
Neural network first guess reconstruction

Work: Justin Albury. PhD thesis (2021)



Inputs

3 feature per PMT with S/N > 5σ



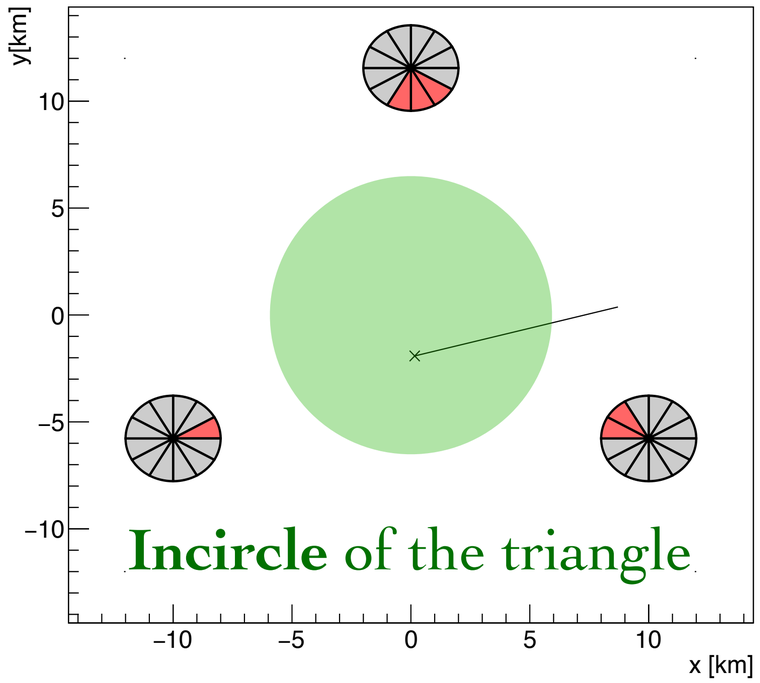
Outputs

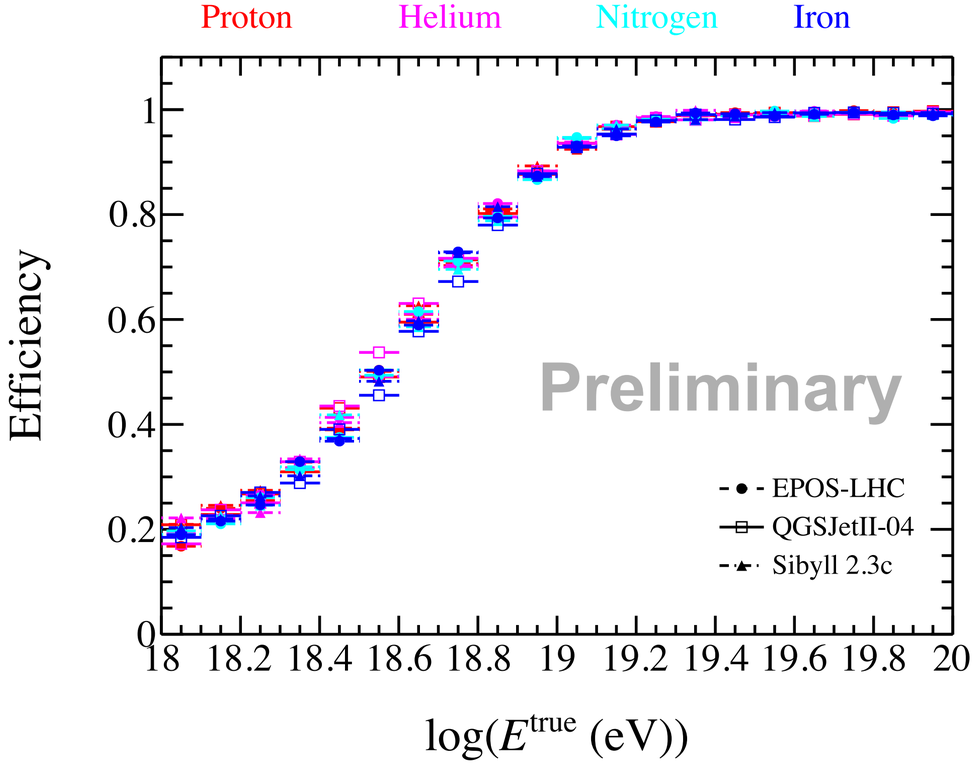
Energy, Xmax, geometry(θ, φ, x, y)

- **Top-down reconstruction (Inverse Monte Carlo)**
  - Use all available information from individual pixel traces
    - Computationally expensive
    - Need a reliable first-guess geometry
- **Neural network first guess reconstruction**
  - 3 input per PMT: **total signal, centroid time and pulse hight**
    - Kares/Tensorflow in Python, two hidden layers
  - 6 outputs: X_{max}, energy, geometry (θ, φ, x, y)
    - Very prompt reconstruction

Performance 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)





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

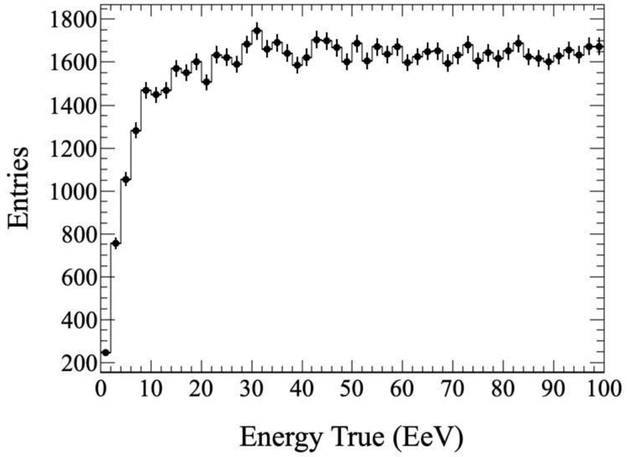
3-fold trigger efficiency

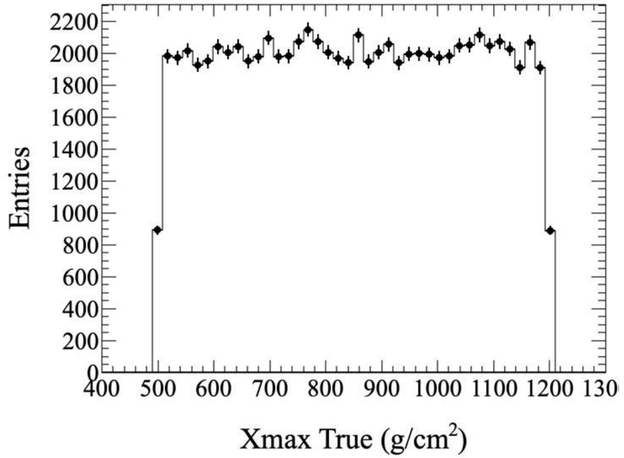
100% above $10^{19.3}$ eV

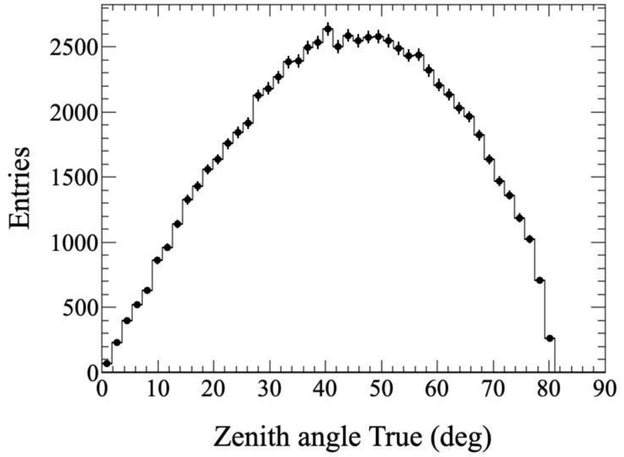
EASTROC
Fluorescence detector Array of Single-pixel Telescopes

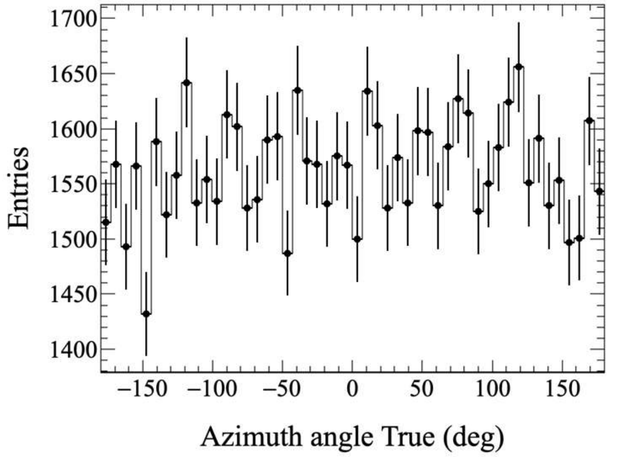
Parameter distributions (3-fold events w/o quality cuts)

True parameters

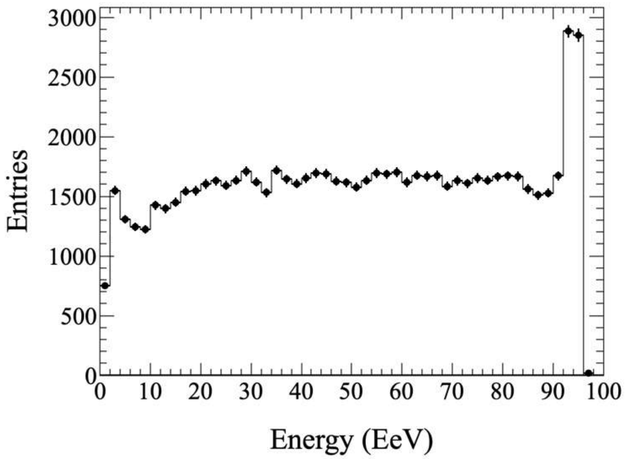


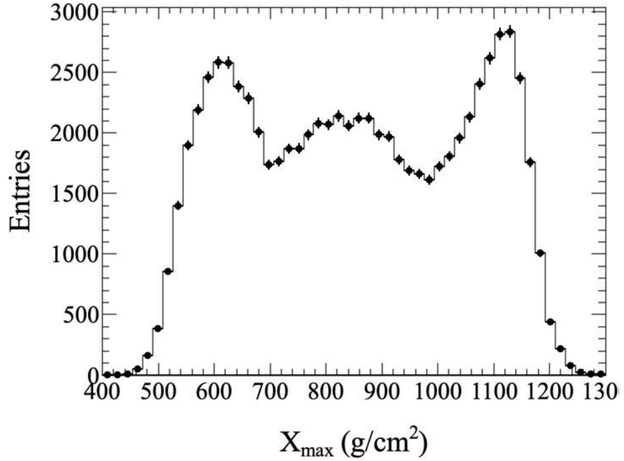


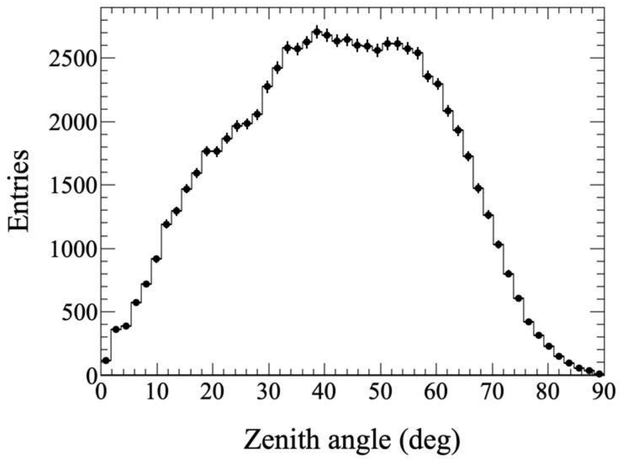


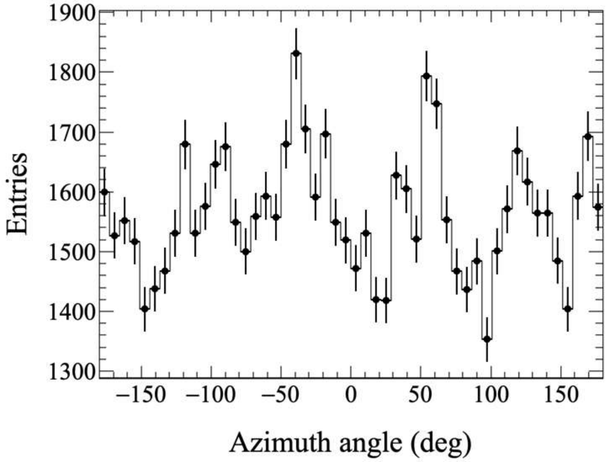


Reconstructed parameters



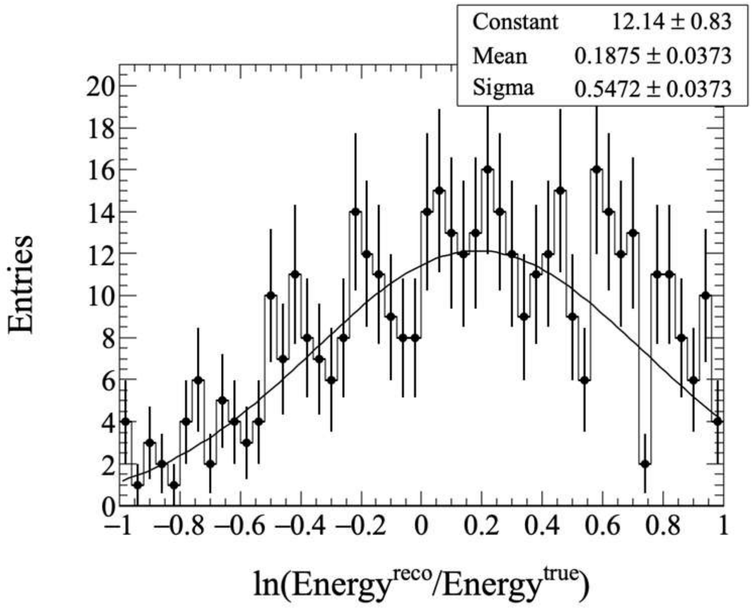


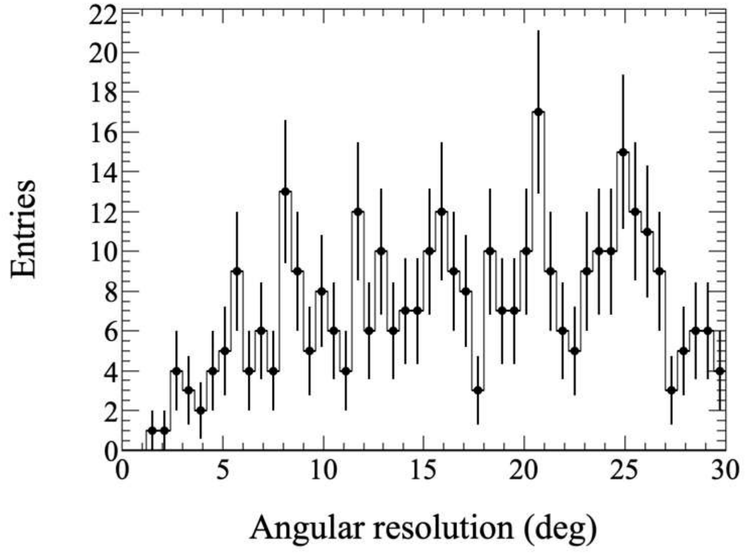


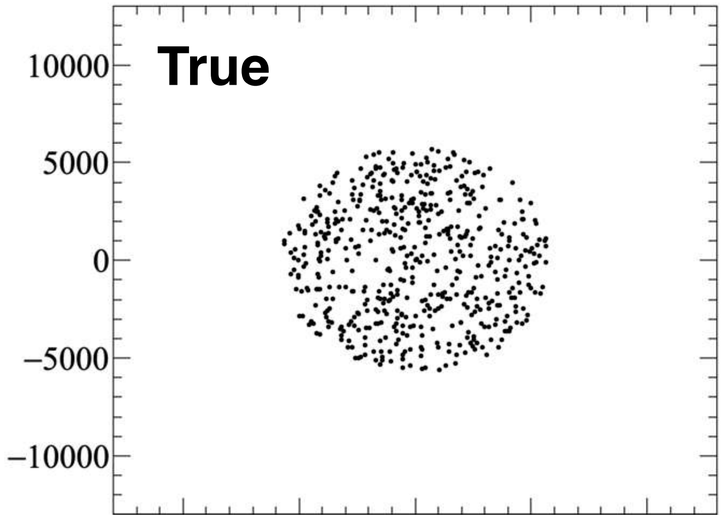


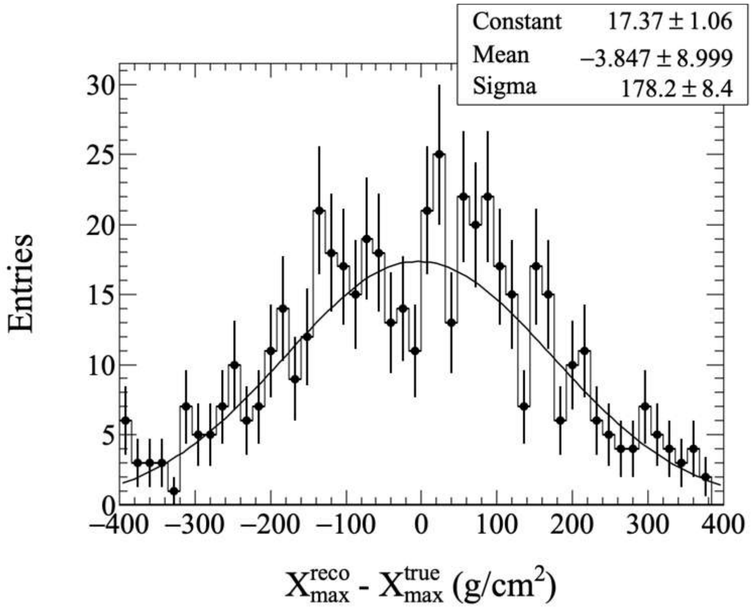
EAST
Fluorescence detector Array of Single-pixel Telescopes

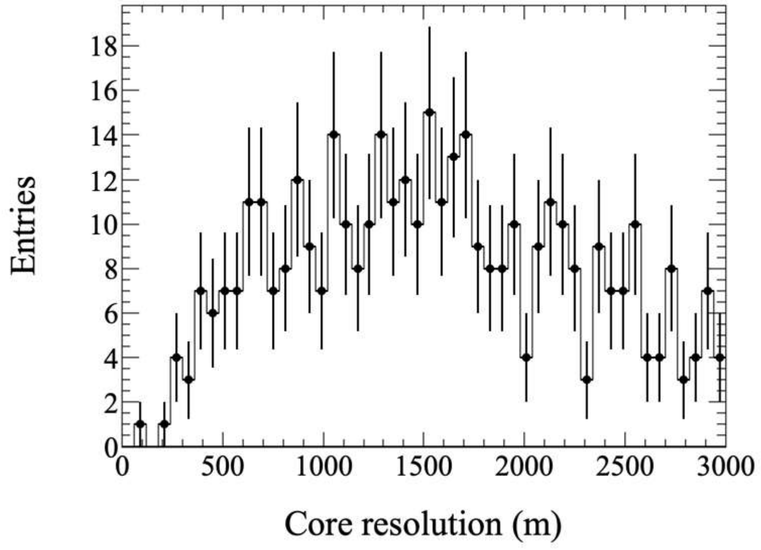
1 - 3 EeV

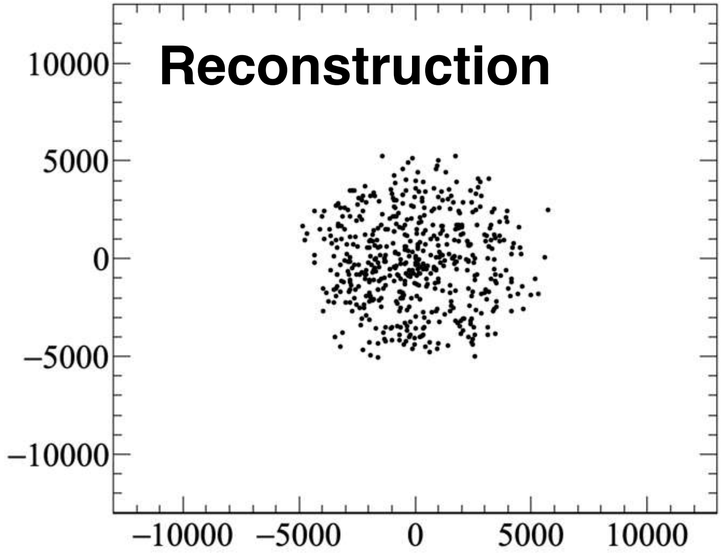






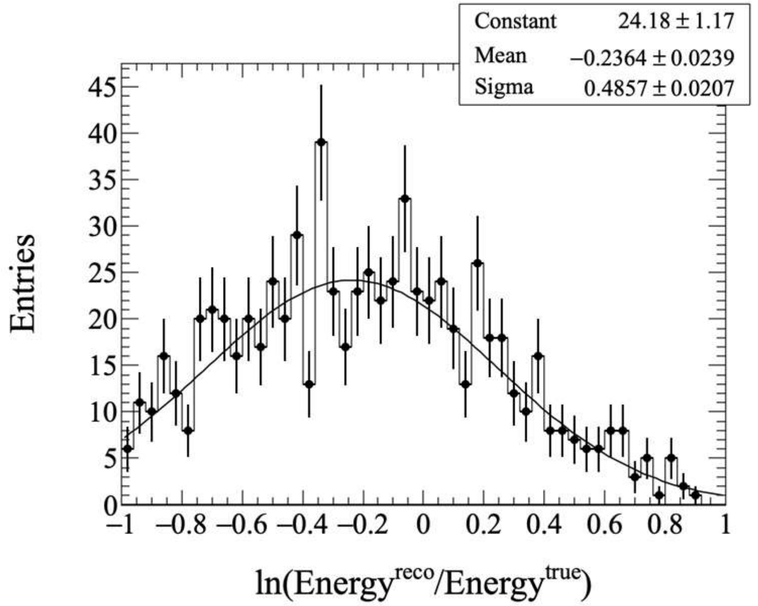


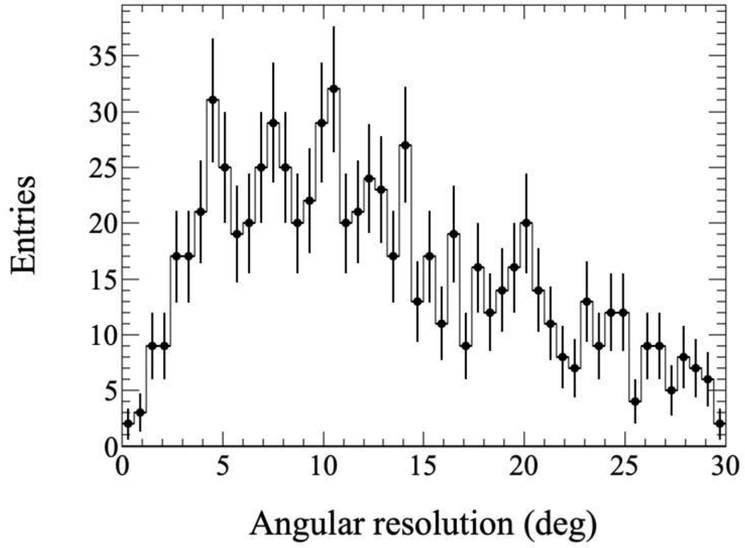


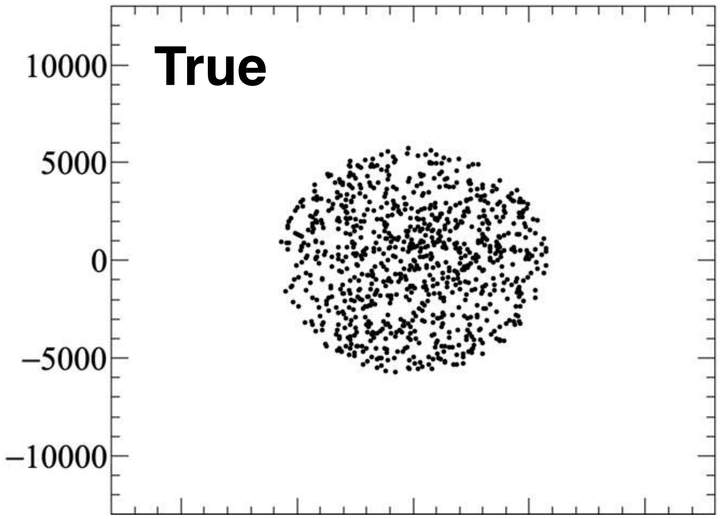


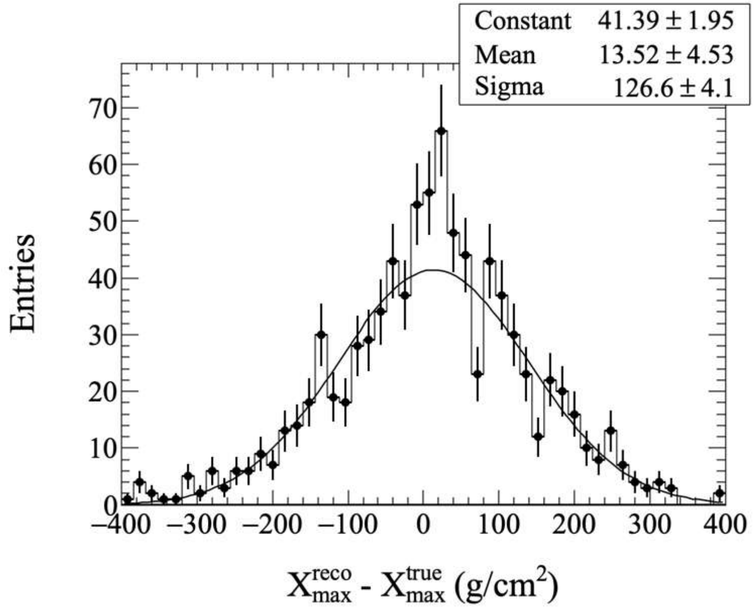
EAST
Fluorescence detector Array of Single-pixel Telescopes

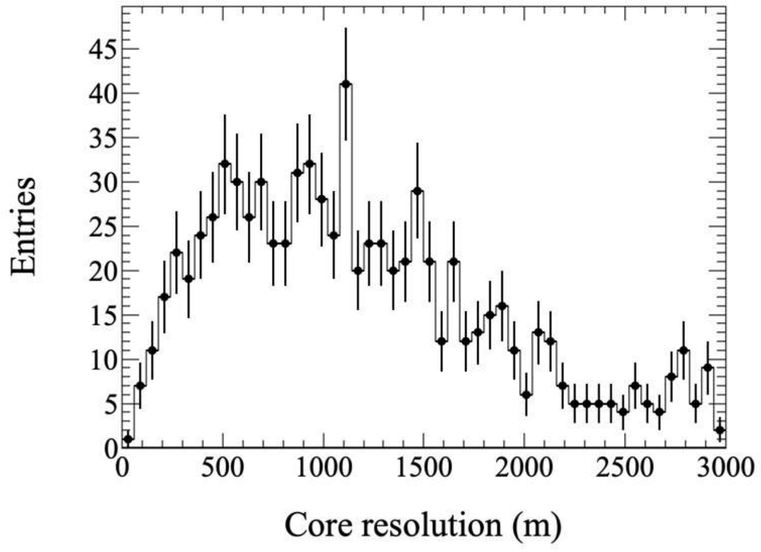
3 - 5 EeV

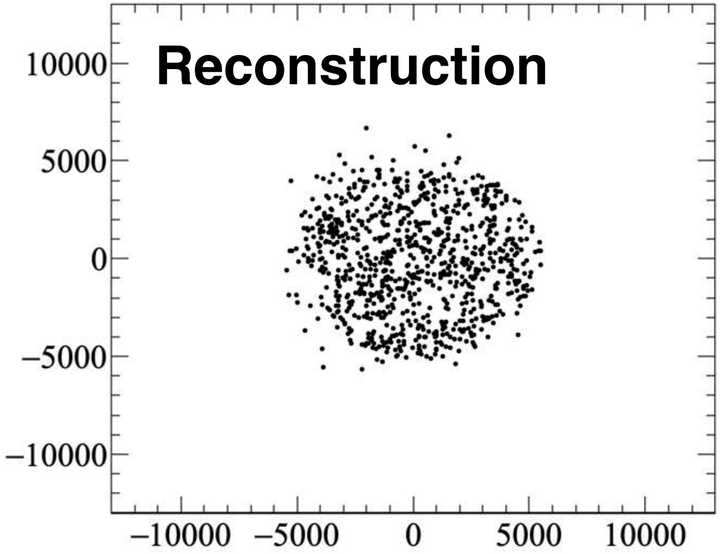




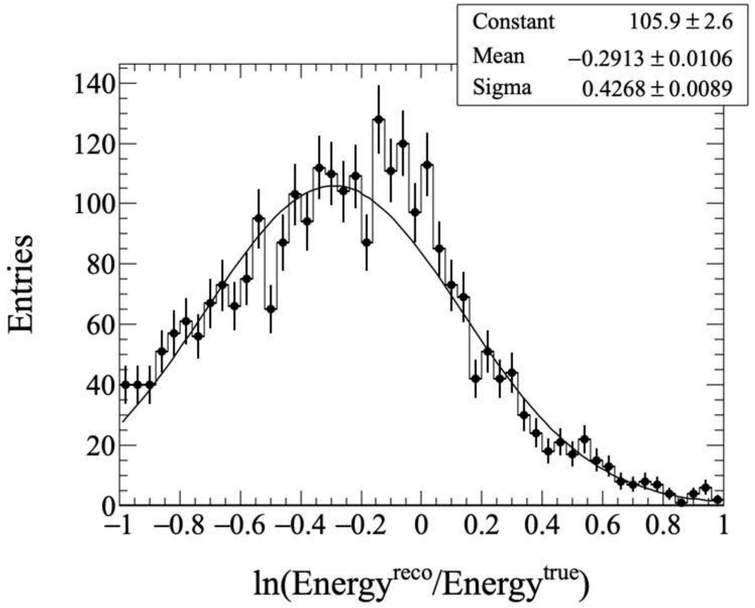


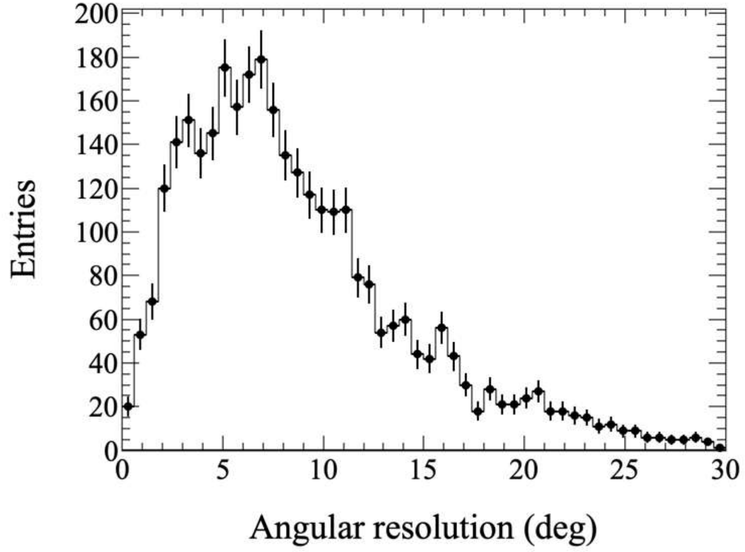


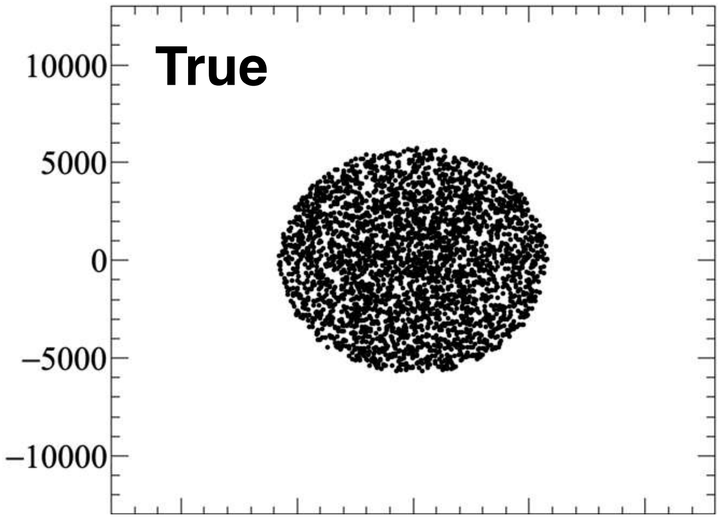


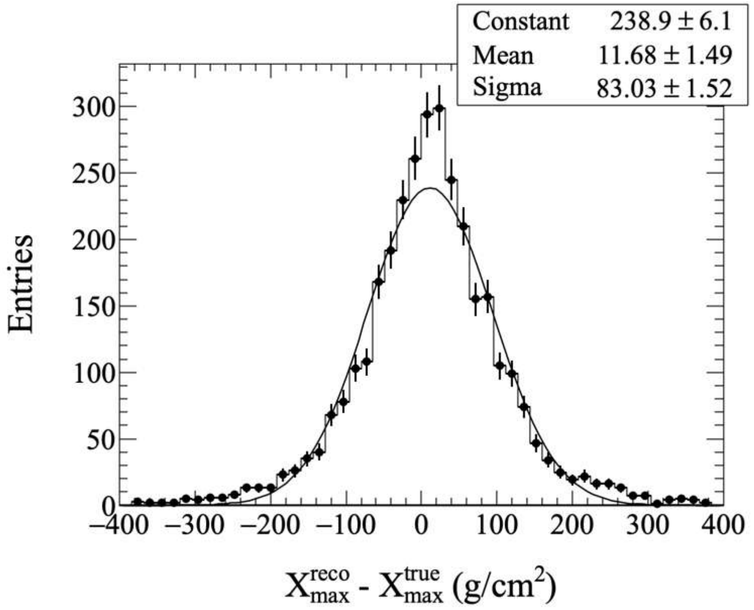


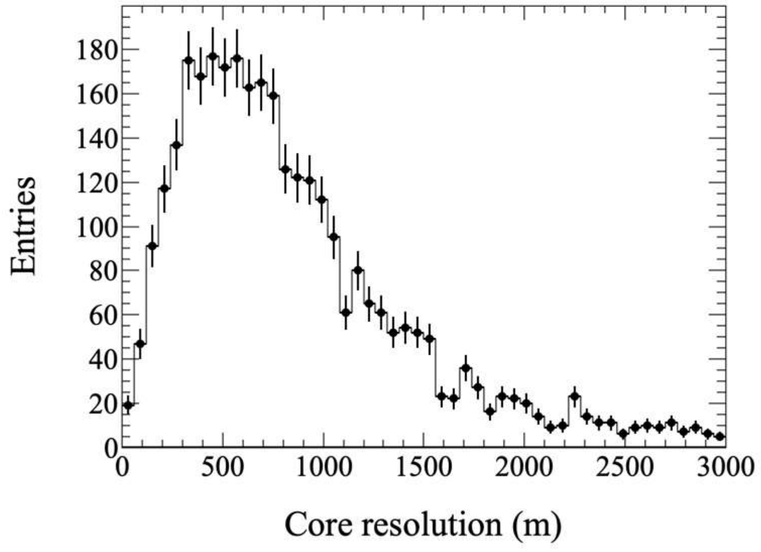
5 - 10 EeV

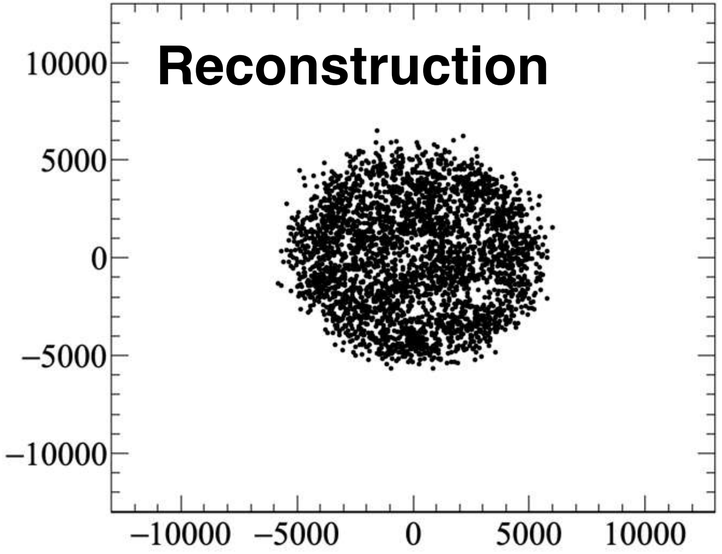

Constant 105.9 ± 2.6
Mean −0.2913 ± 0.0106
Sigma 0.4268 ± 0.0089
Entries
ln(Energy^reco/Energy^true)


Entries
Angular resolution (deg)

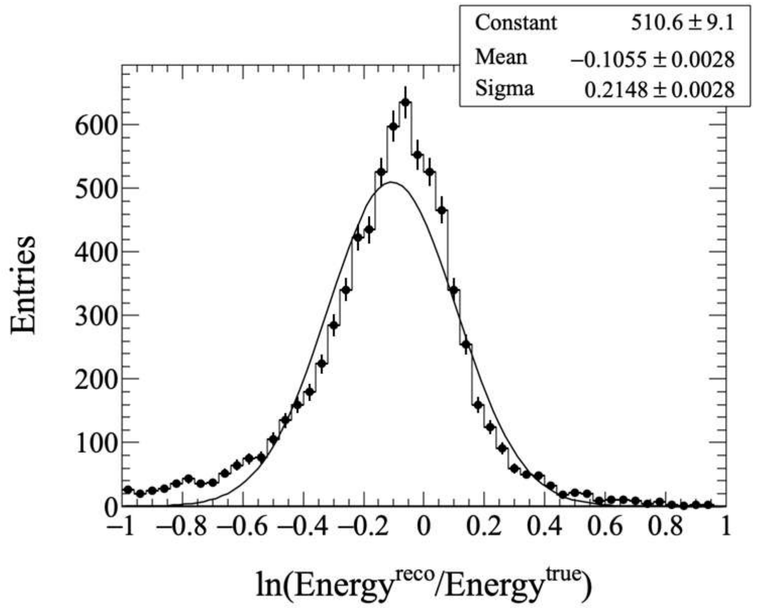

True

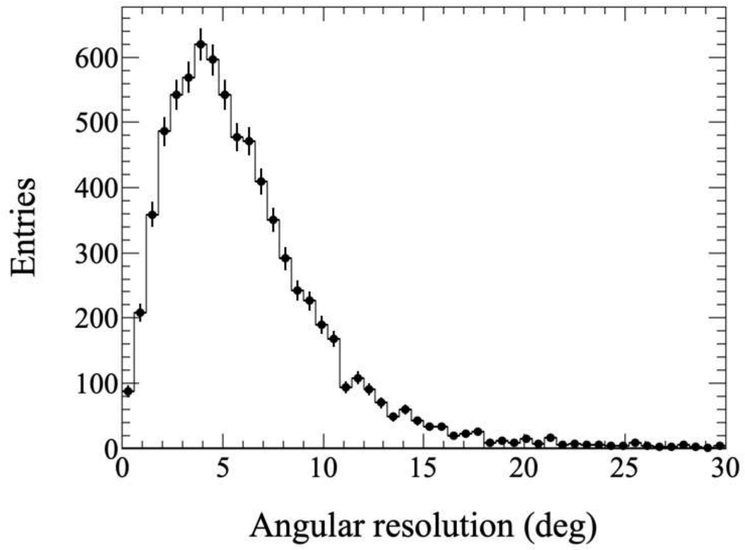

Constant 238.9 ± 6.1
Mean 11.68 ± 1.49
Sigma 83.03 ± 1.52
Entries
X^reco_max - X^true_max (g/cm²)

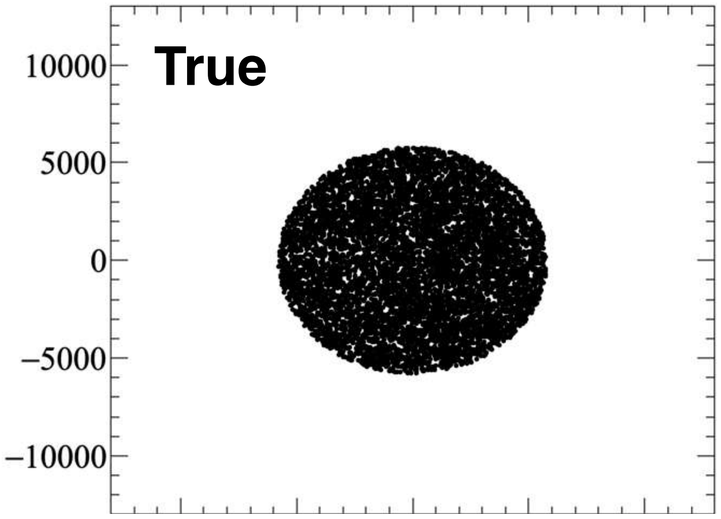

Entries
Core resolution (m)

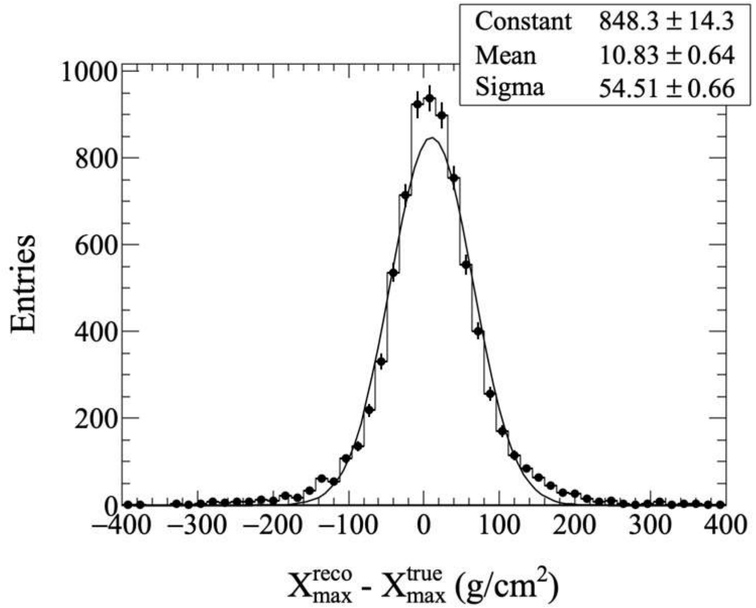

Reconstruction

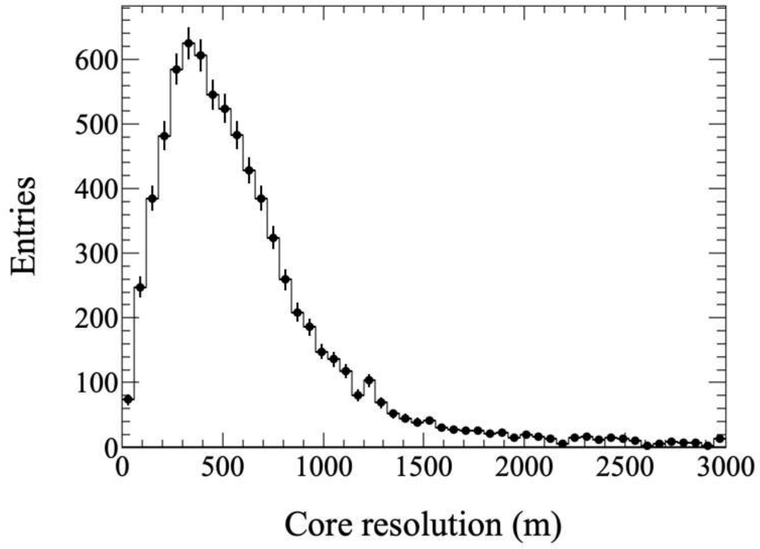
10 - 20 EeV

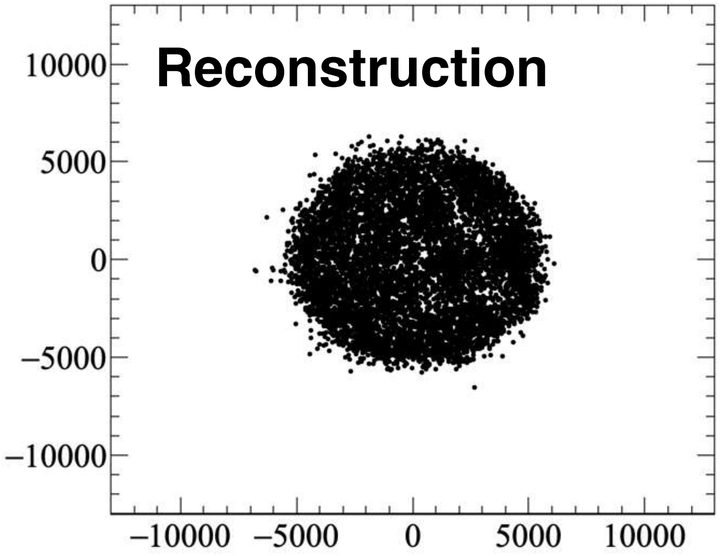

Constant 510.6 ± 9.1
Mean −0.1055 ± 0.0028
Sigma 0.2148 ± 0.0028
Entries
ln(Energy^reco/Energy^true)


Entries
Angular resolution (deg)


True

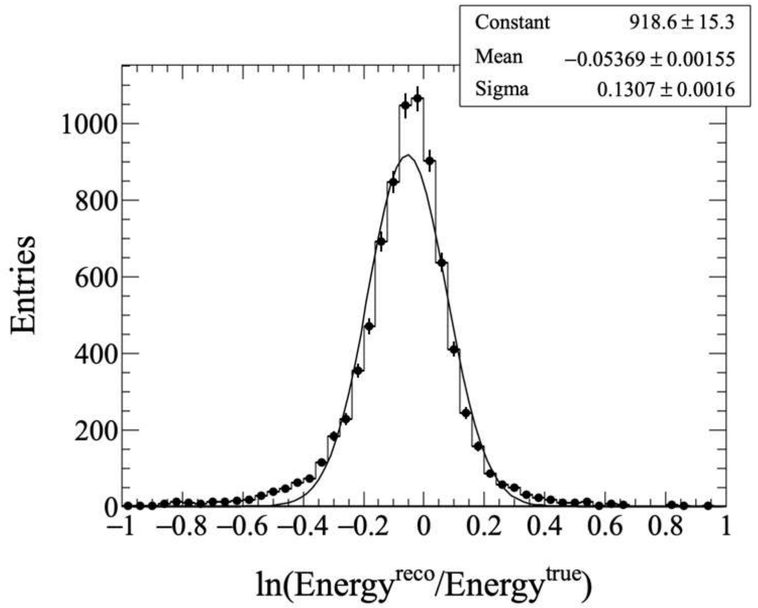

Constant 848.3 ± 14.3
Mean 10.83 ± 0.64
Sigma 54.51 ± 0.66
Entries
X^reco_max - X^true_max (g/cm²)

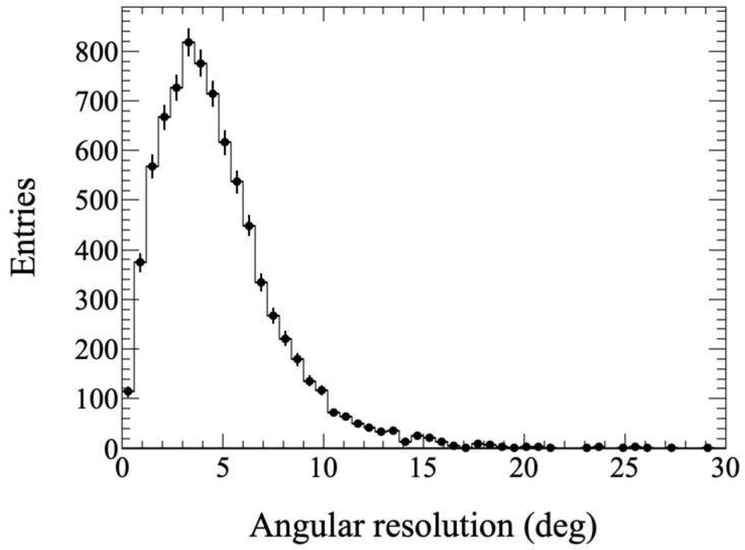

Entries
Core resolution (m)

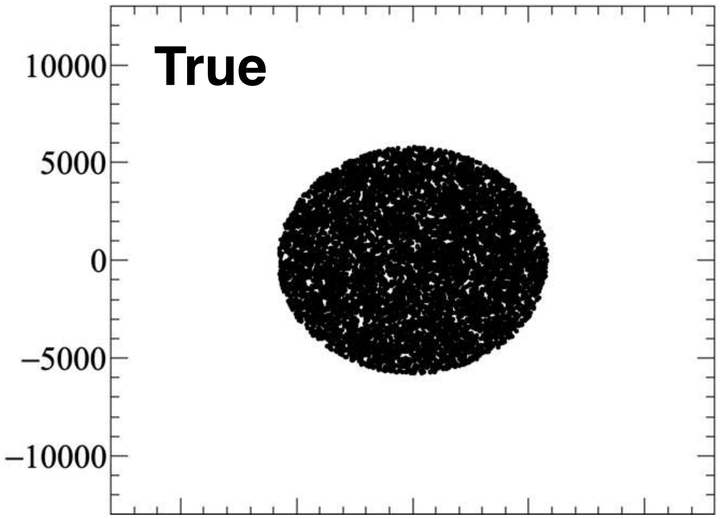

Reconstruction

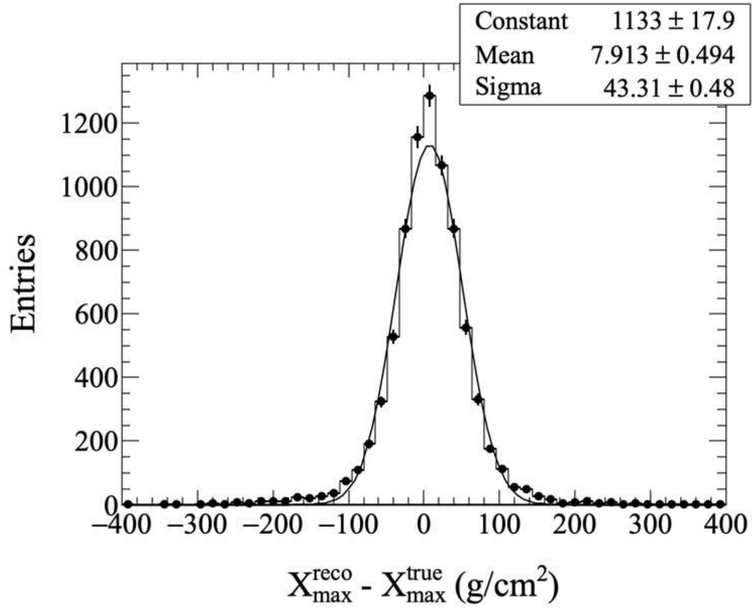
EAST
Fluorescence detector Array of Single-pixel Telescopes

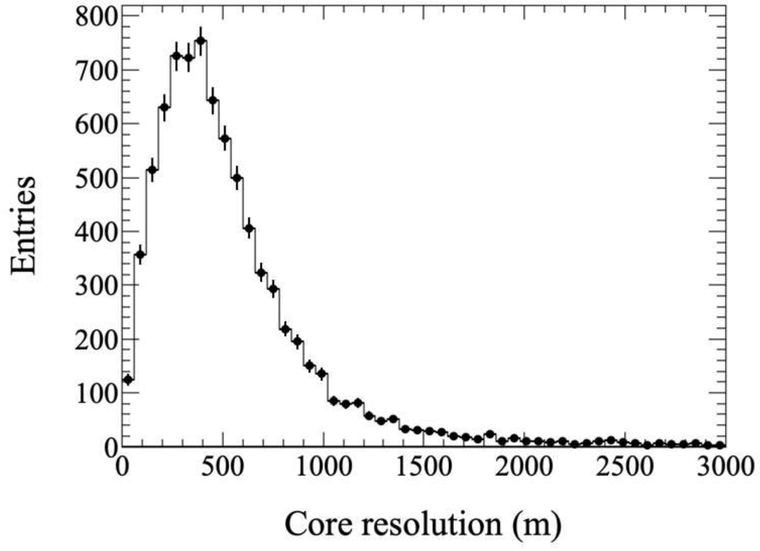
20 - 30 EeV

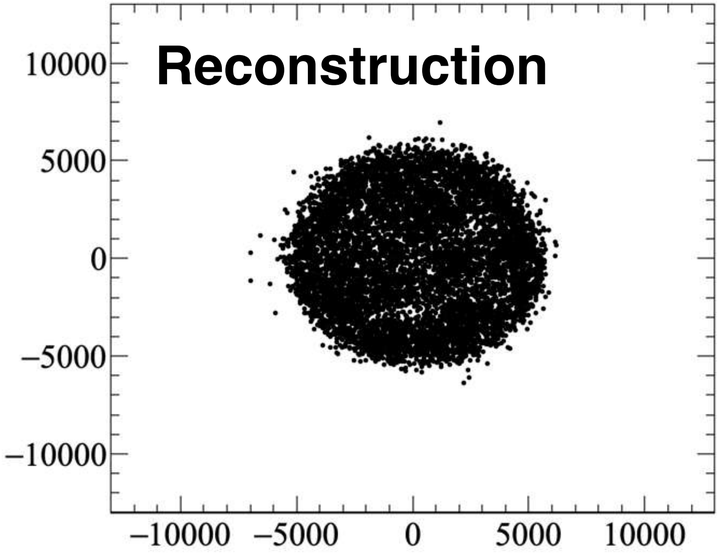




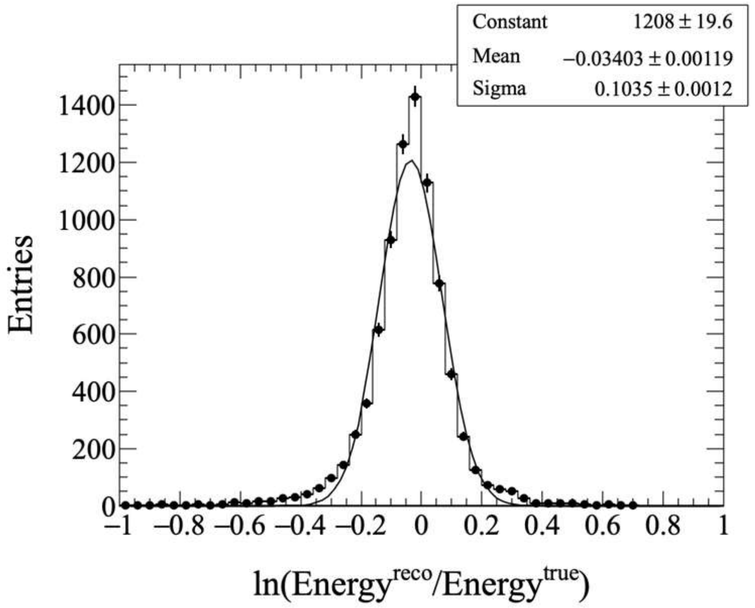


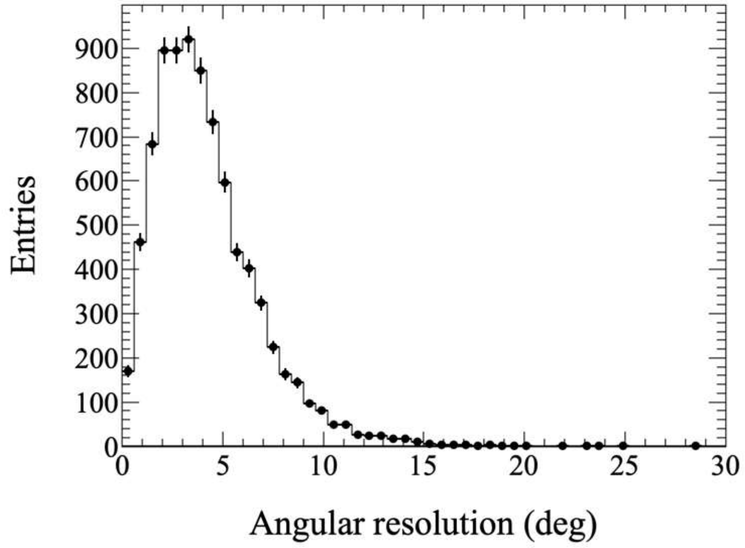


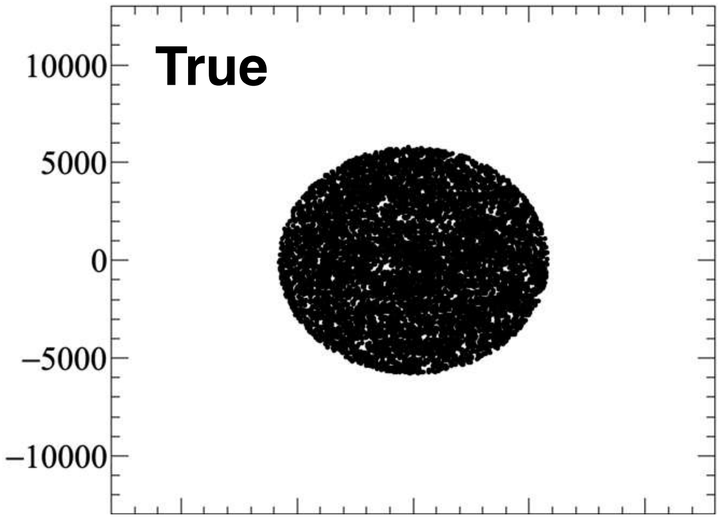


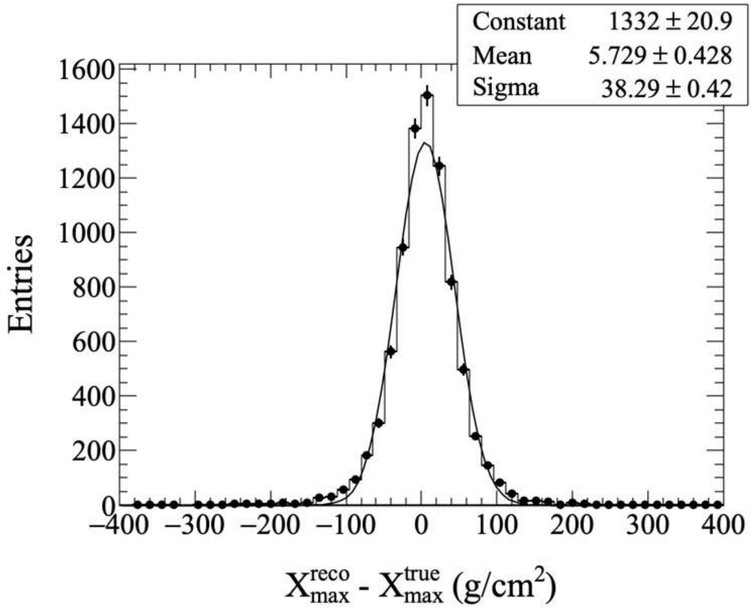


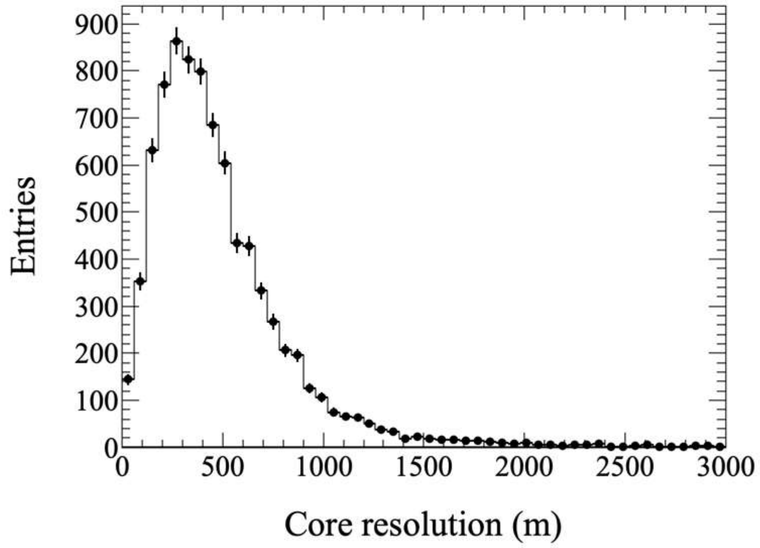
30 - 40 EeV

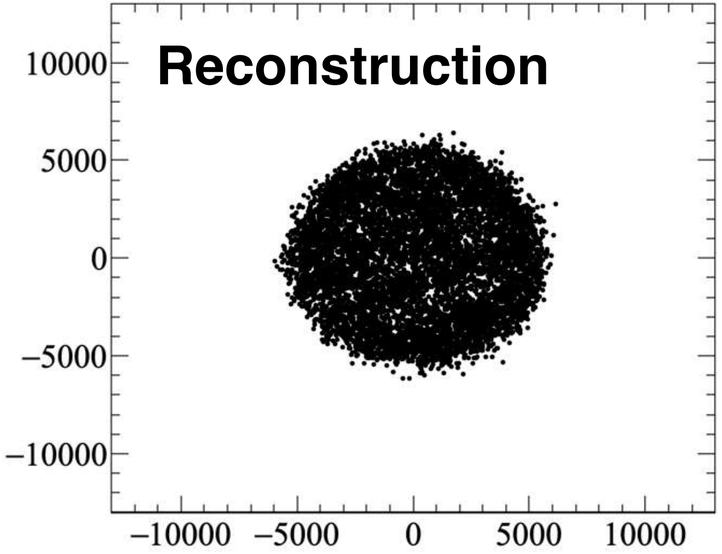

Constant 1208 ± 19.6
Mean −0.03403 ± 0.00119
Sigma 0.1035 ± 0.0012
Entries
ln(Energy^reco/Energy^true)


Entries
Angular resolution (deg)


True

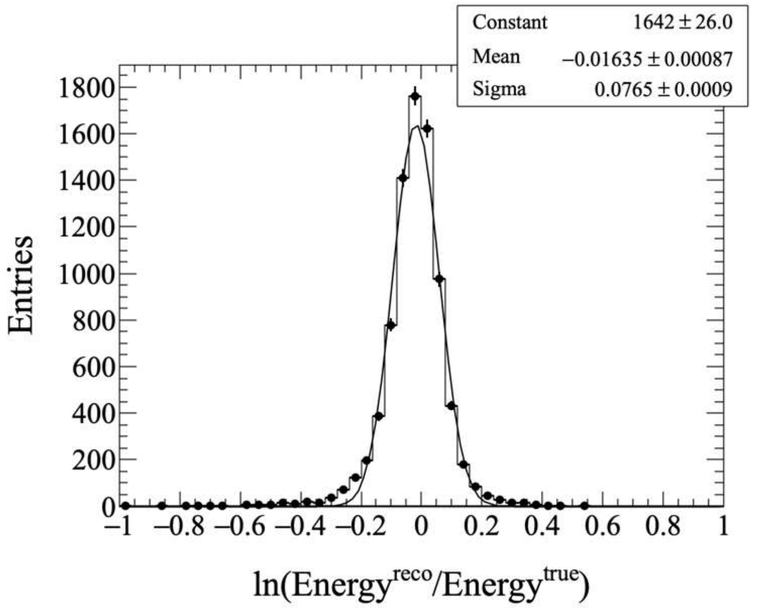

Constant 1332 ± 20.9
Mean 5.729 ± 0.428
Sigma 38.29 ± 0.42
Entries
X^reco_max - X^true_max (g/cm²)

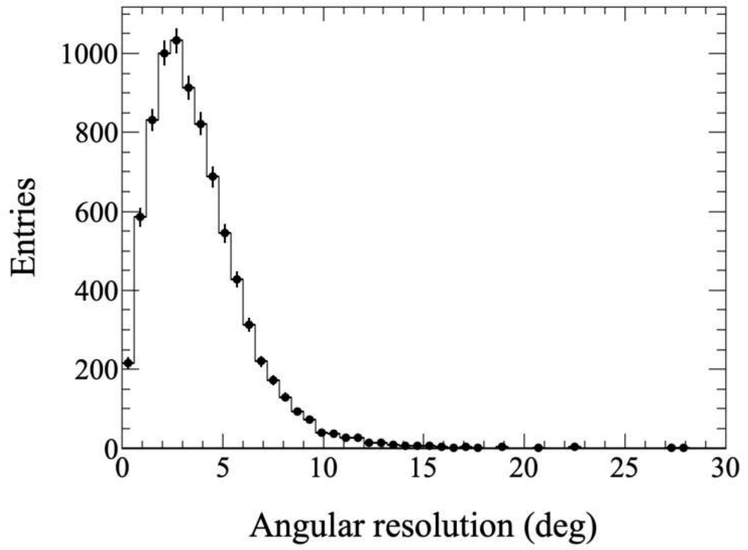

Entries
Core resolution (m)

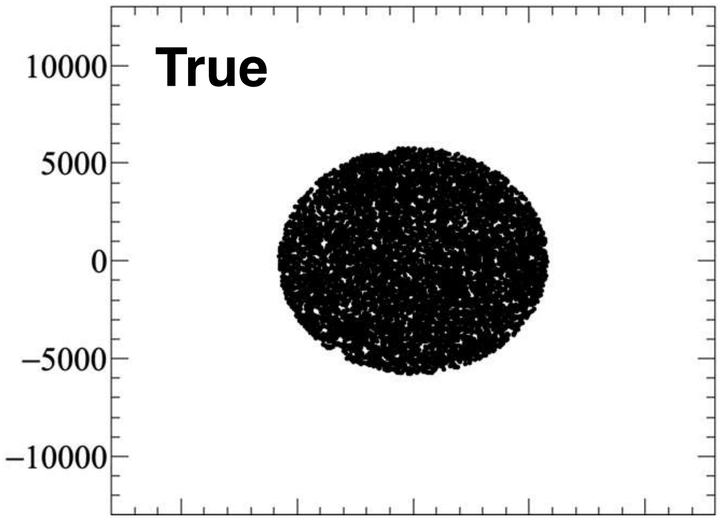

Reconstruction

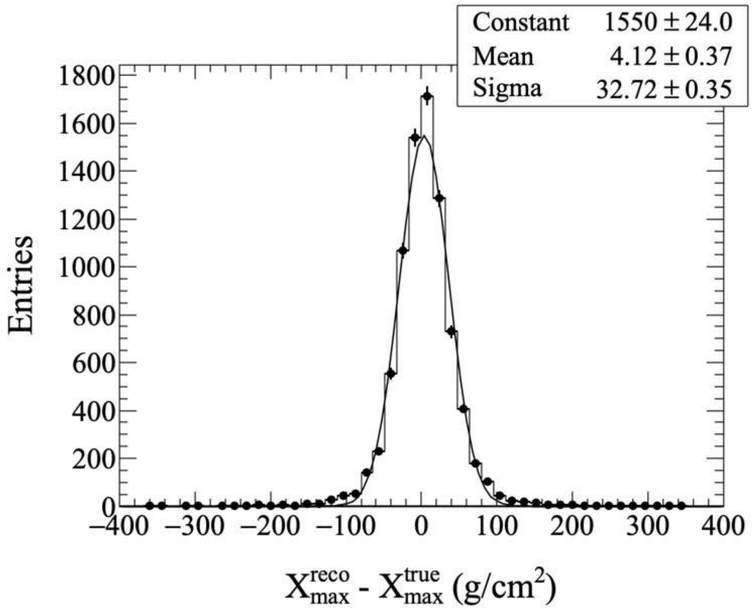
EAST
Fluorescence detector Array of Single-pixel Telescopes

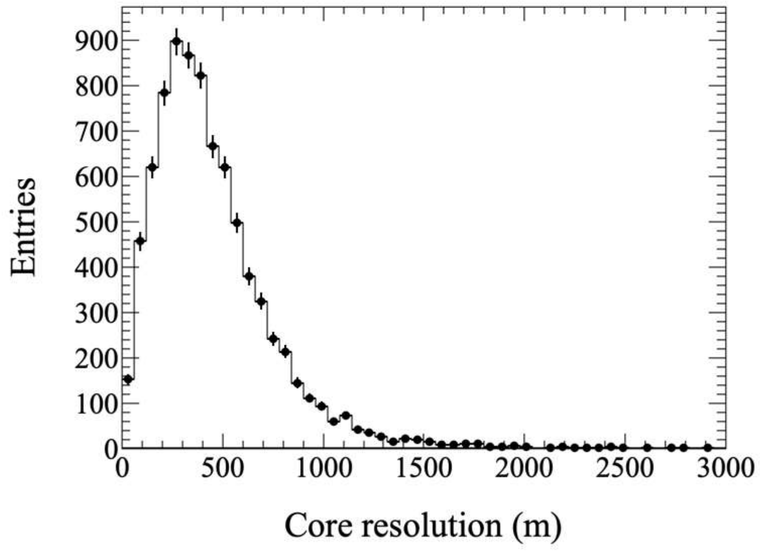
50 - 60 EeV

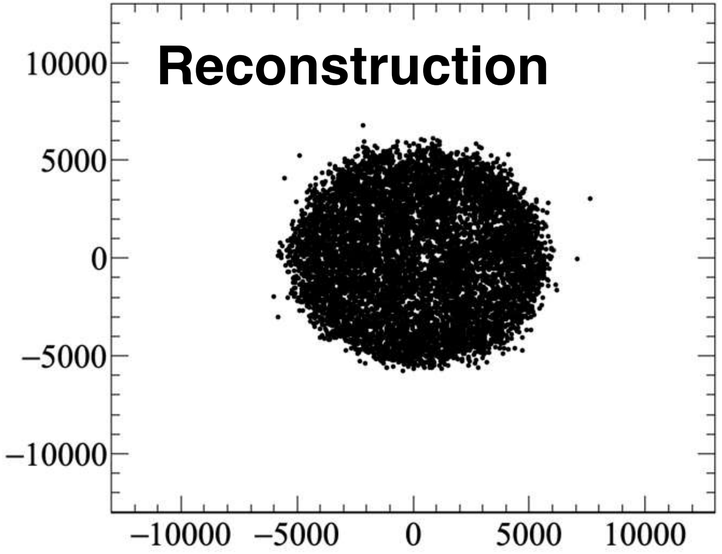






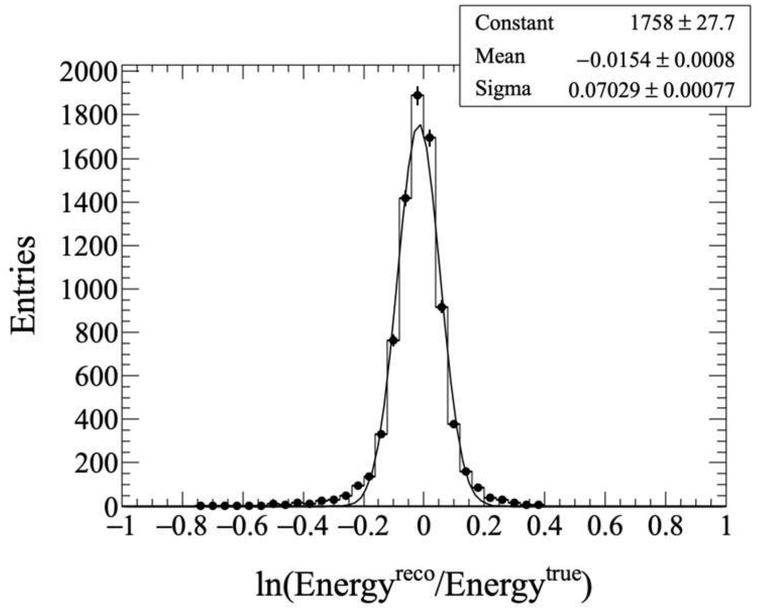


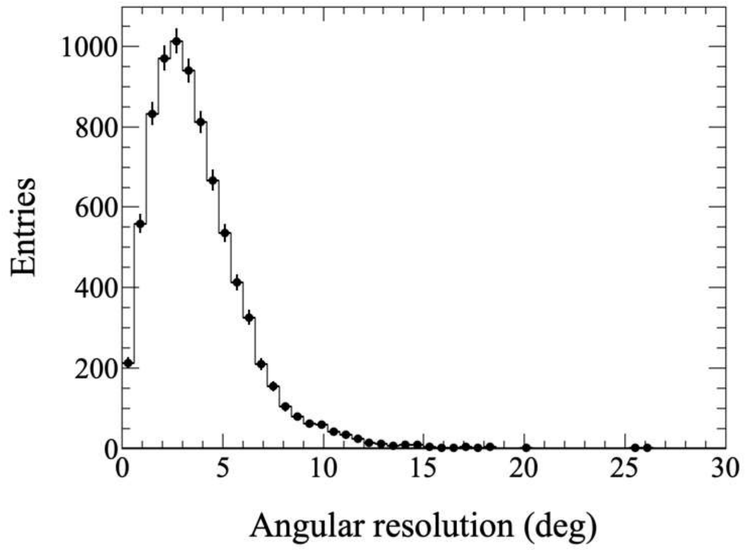


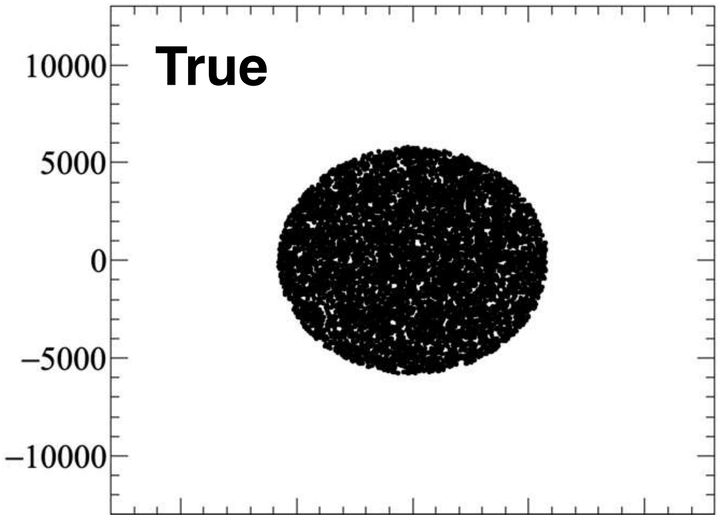


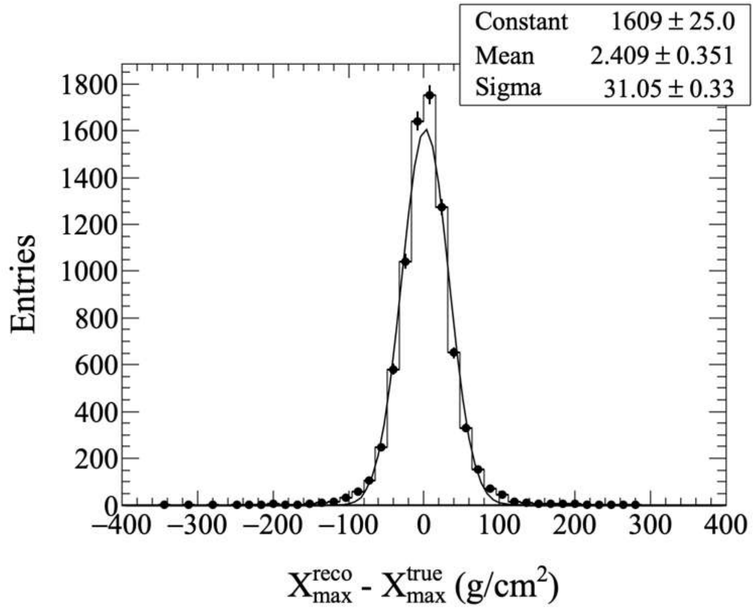
EAST
Fluorescence detector Array of Single-pixel Telescopes

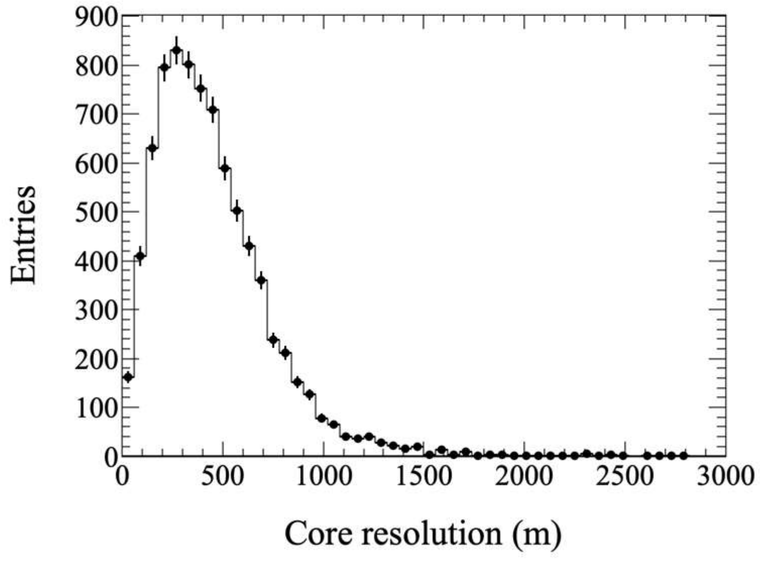
60 - 70 EeV

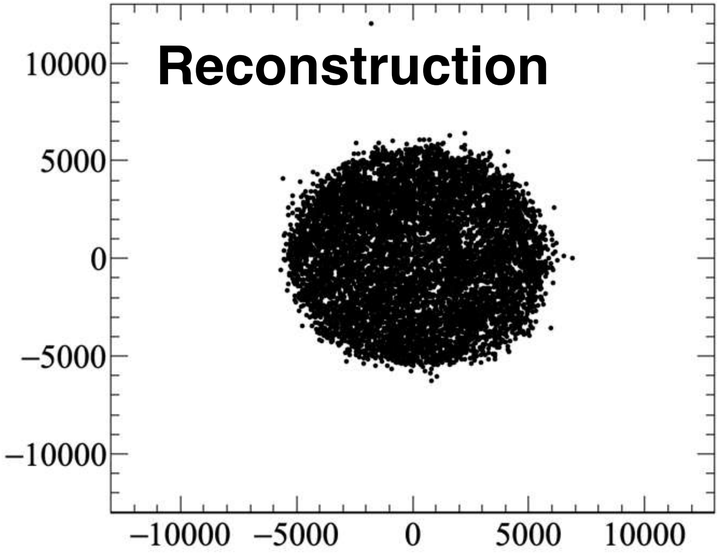






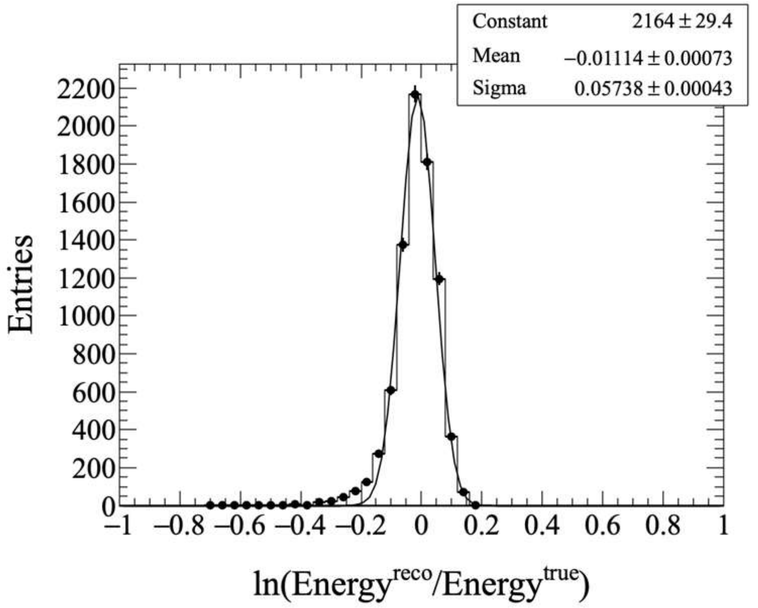


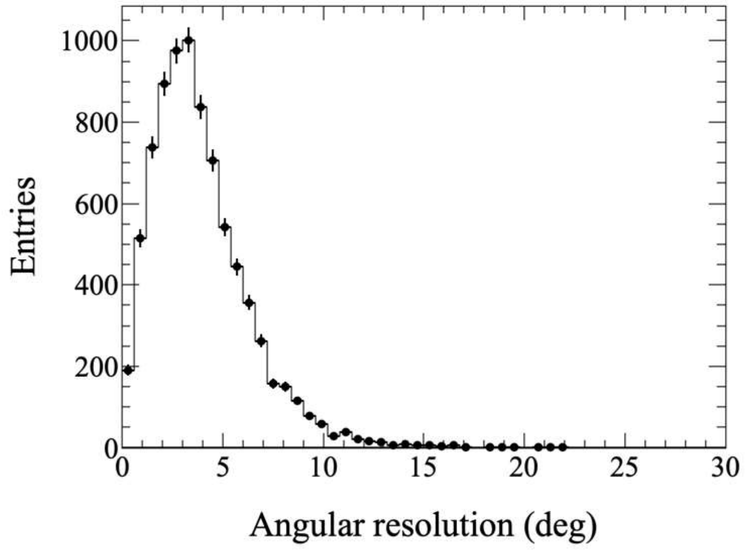


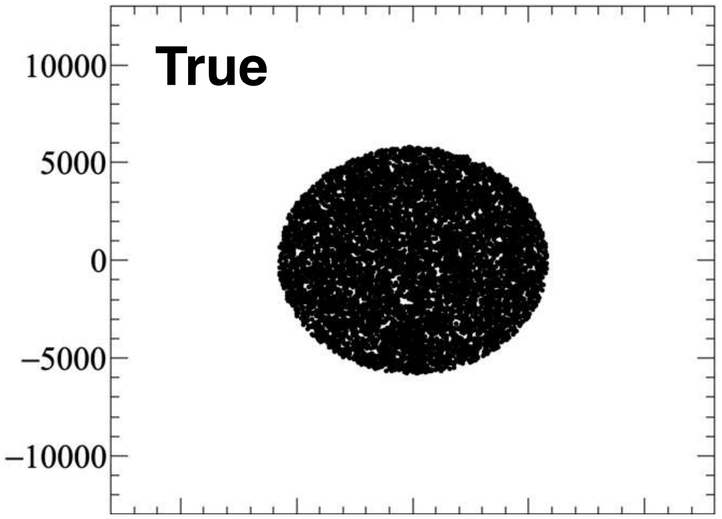


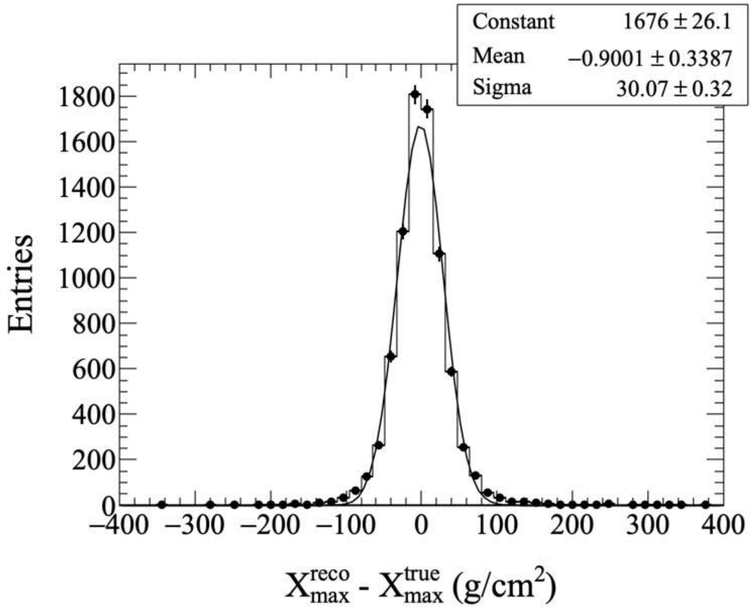
EAST
Fluorescence detector Array of Single-pixel Telescopes

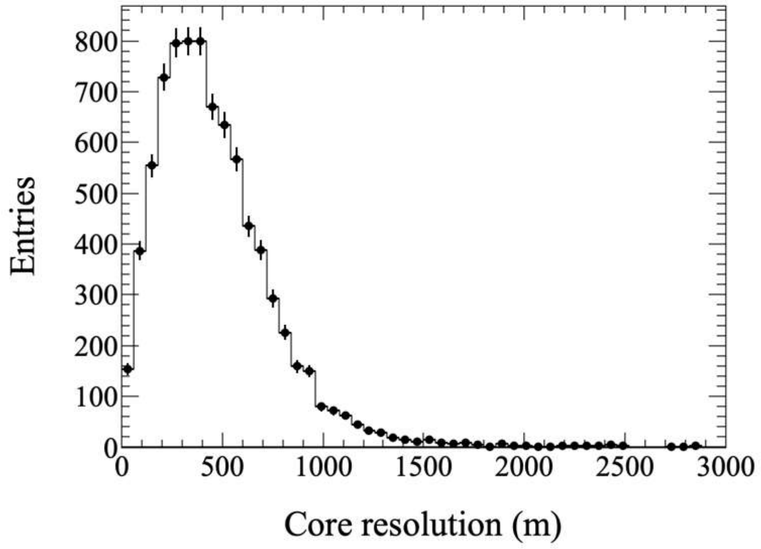
80 - 90 EeV

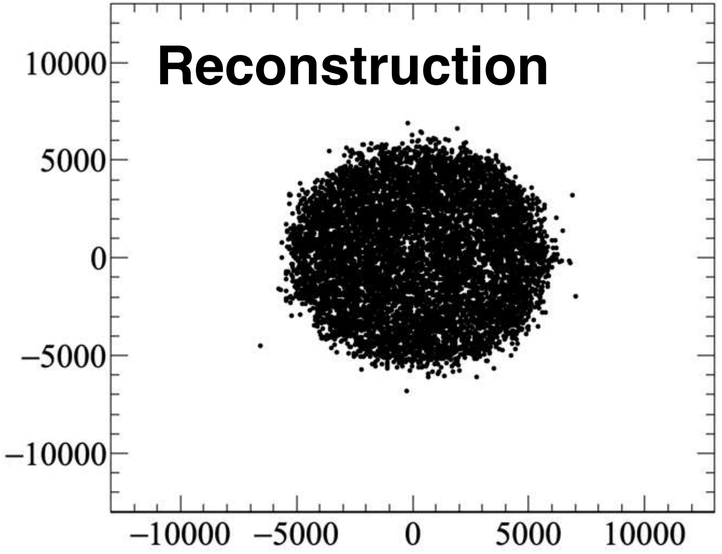






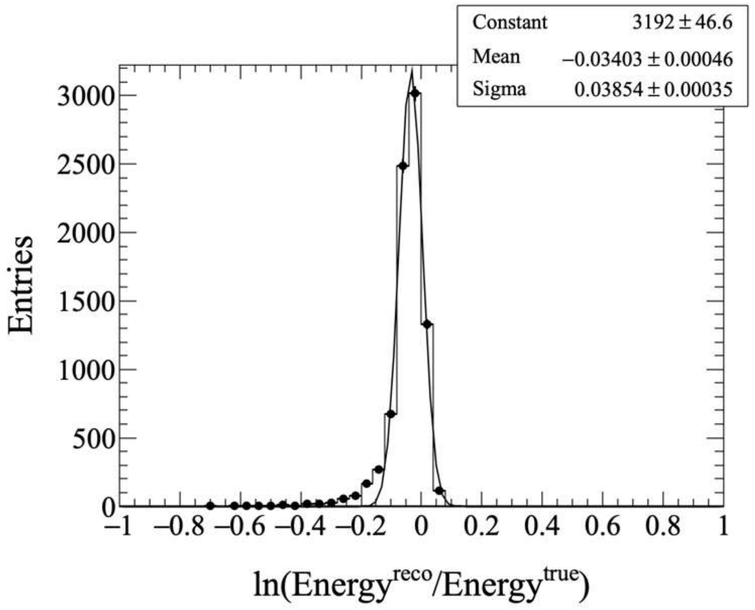


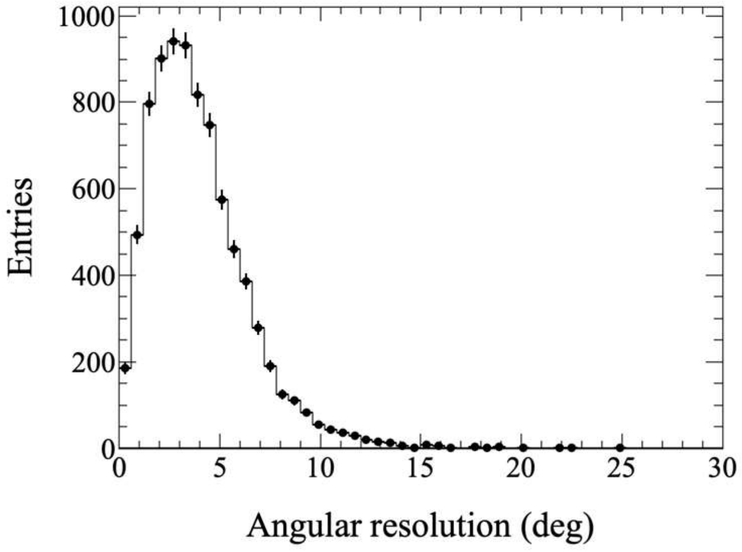


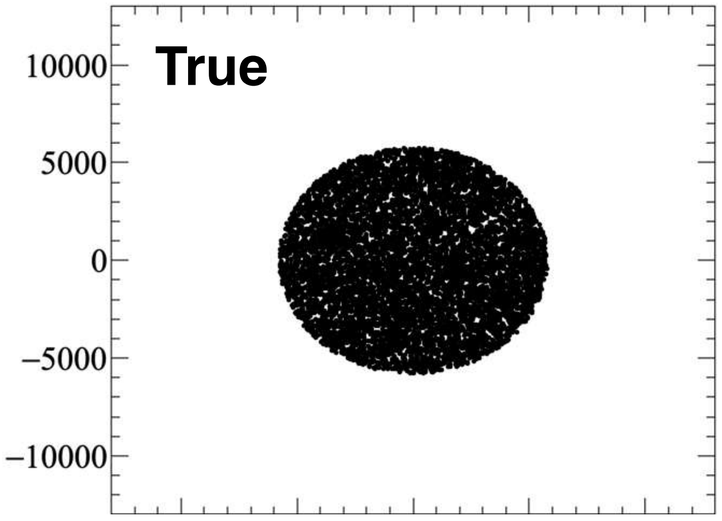


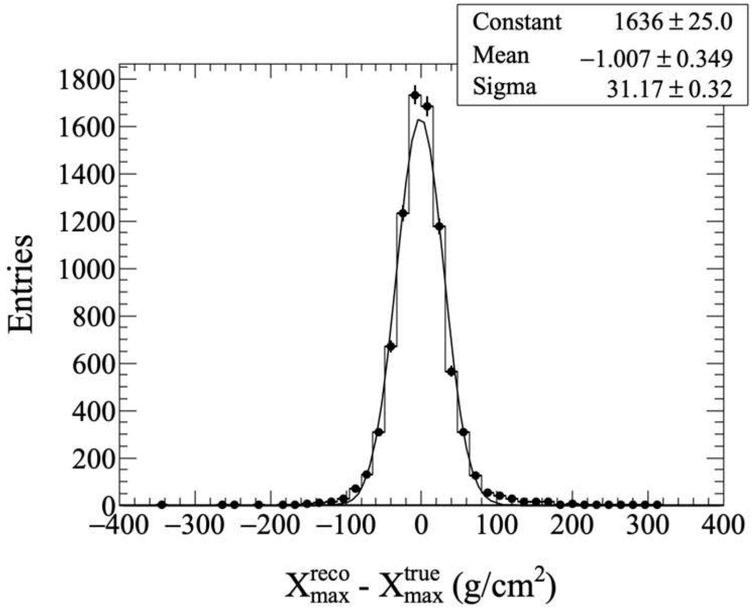
EAST
Fluorescence detector Array of Single-pixel Telescopes

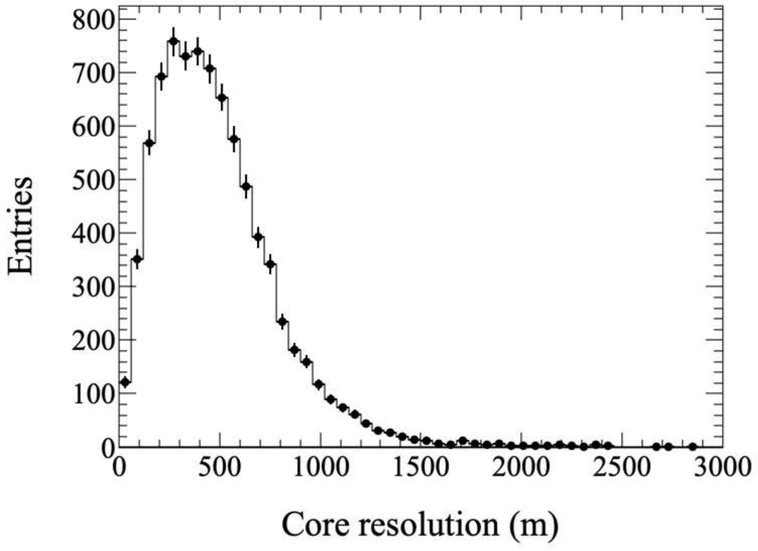
90 - 100 EeV

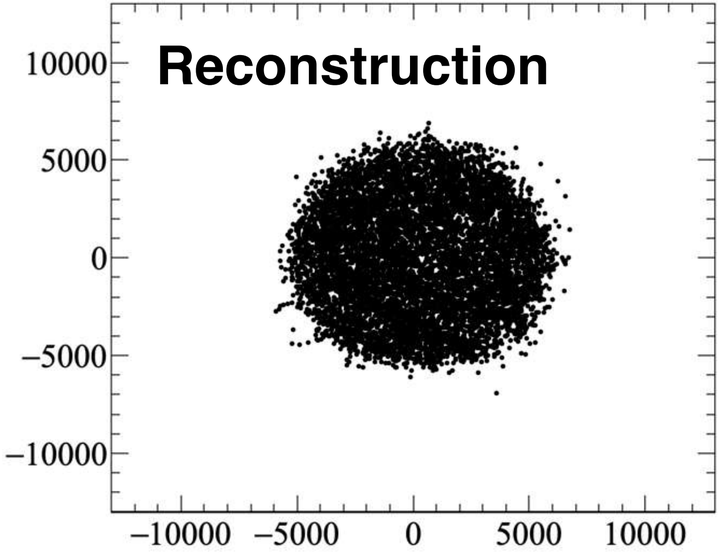




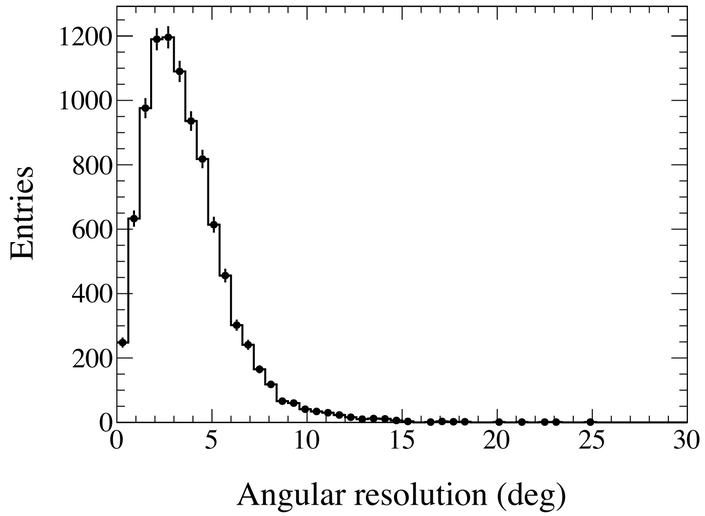


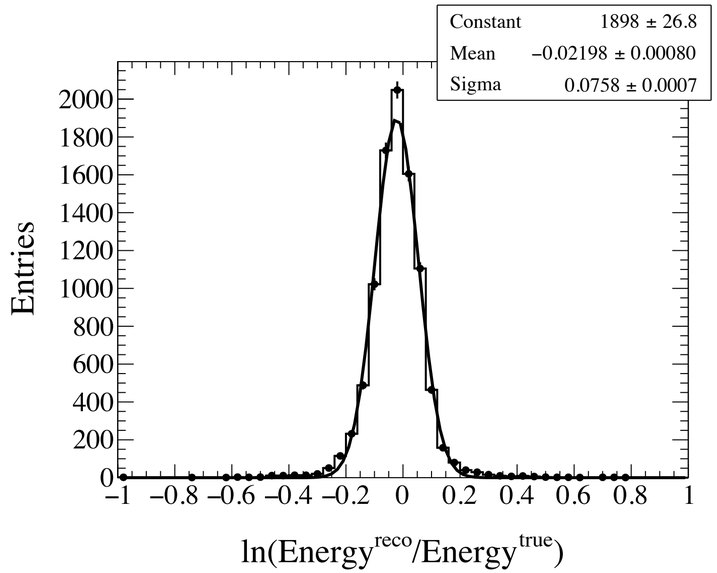


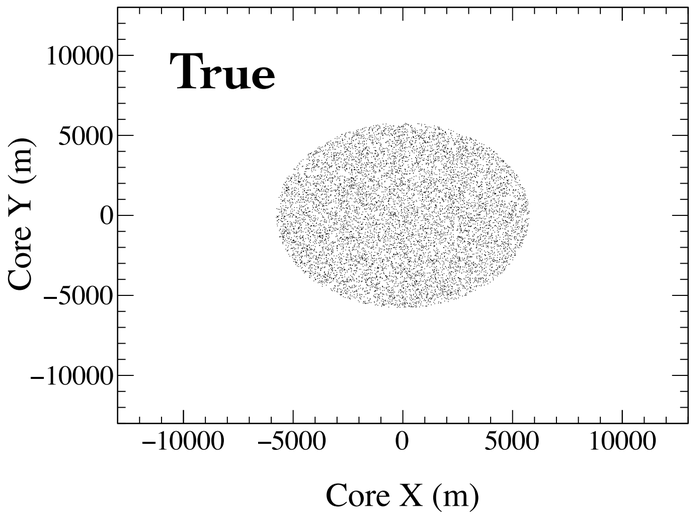


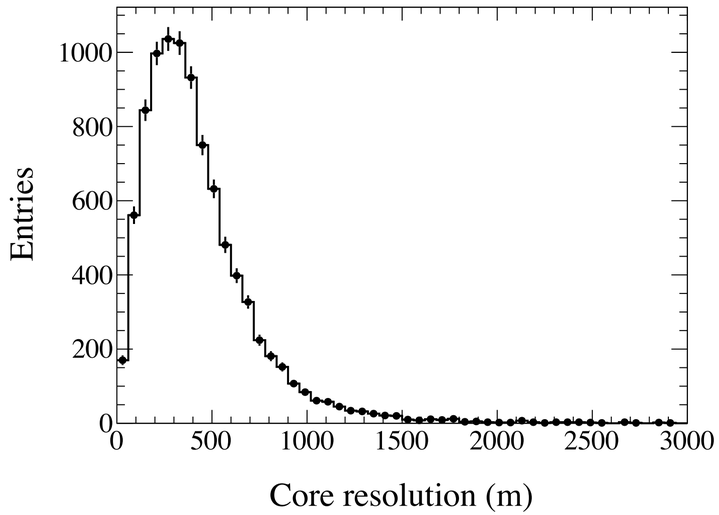


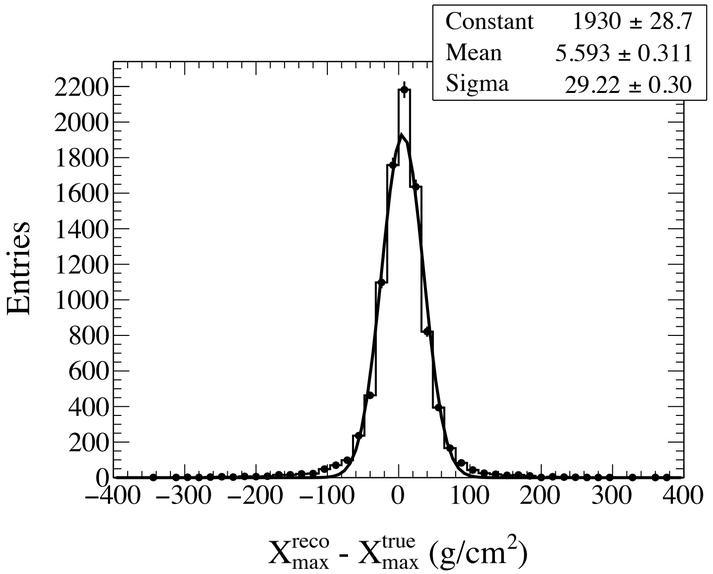
Resolution at 40 - 50 EeV (Proton, EPOS-LHC)

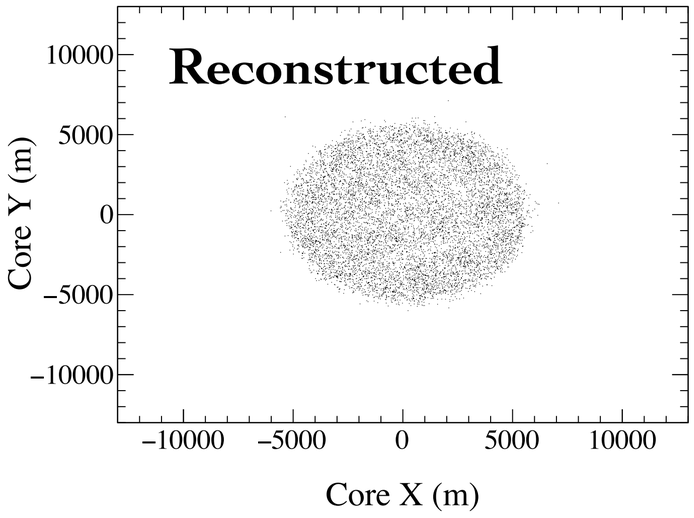








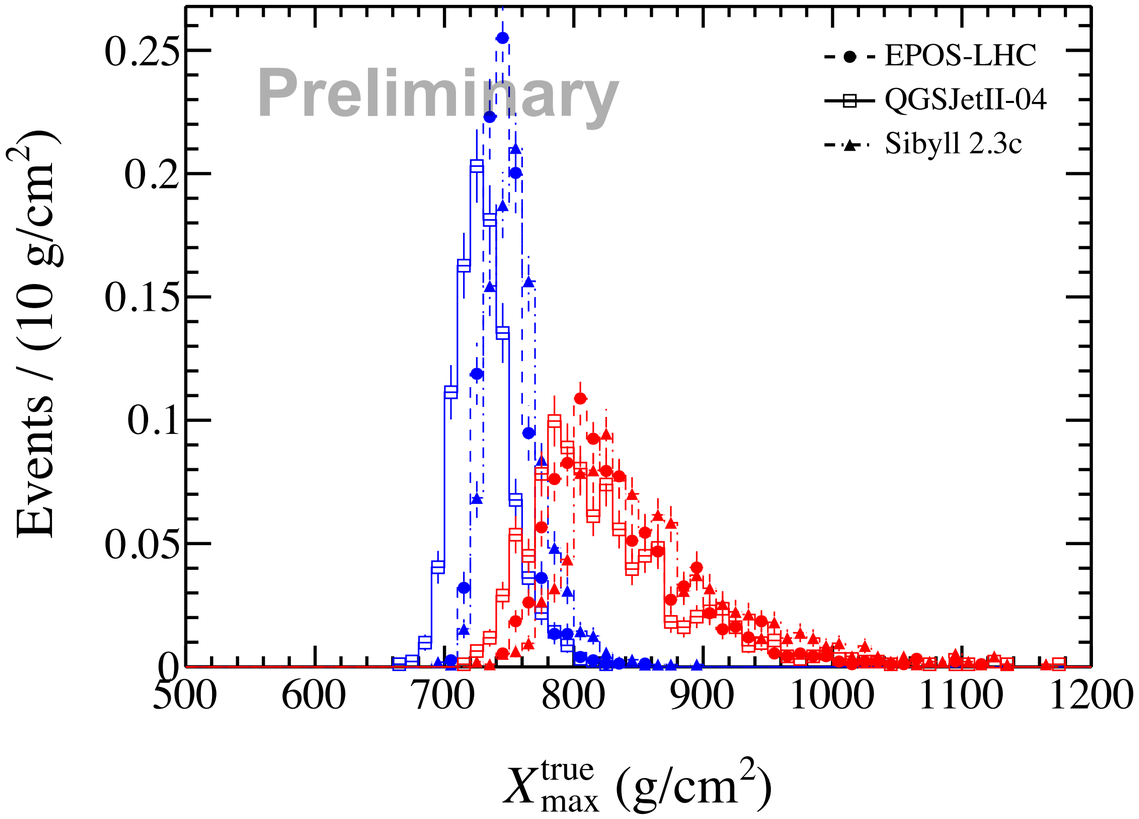




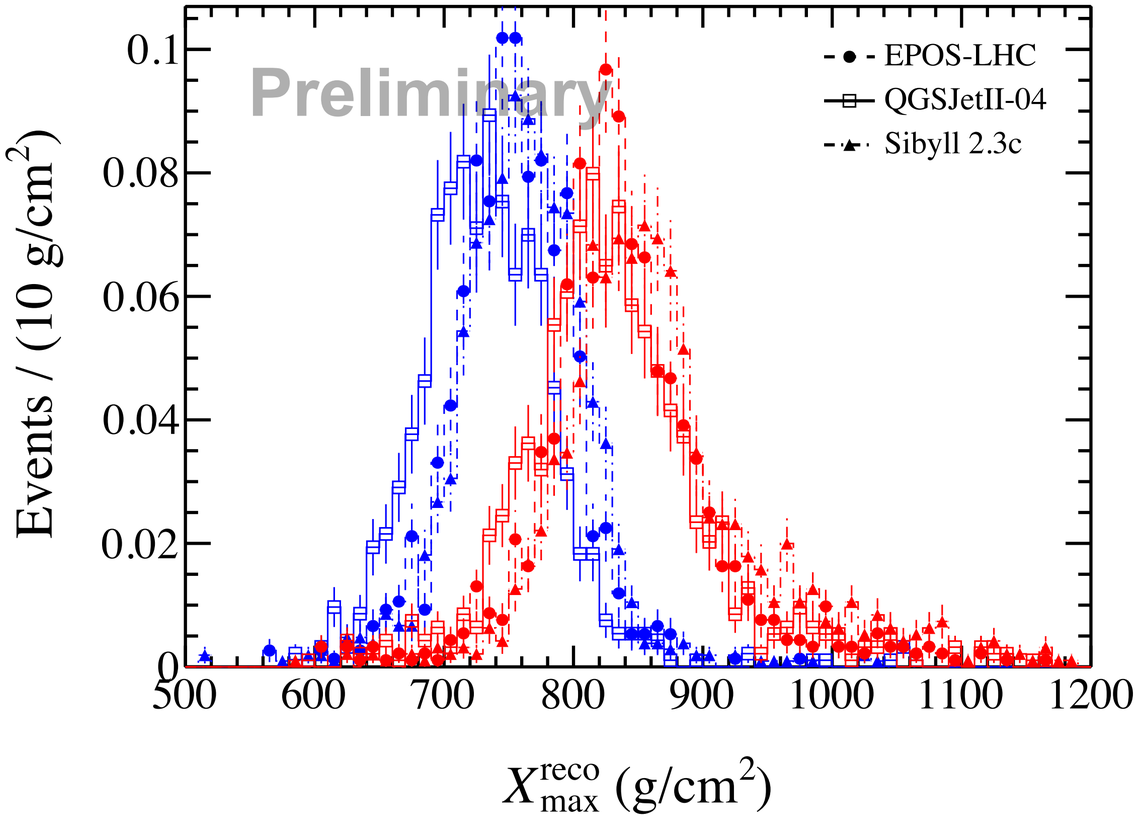
- Arrival direction: 4.2 degrees, Core: 465 m, Energy: 8% Xmax: 30 g/cm² (without quality cuts)

Reconstructed X_{max} distributions at 40 - 50 EeV

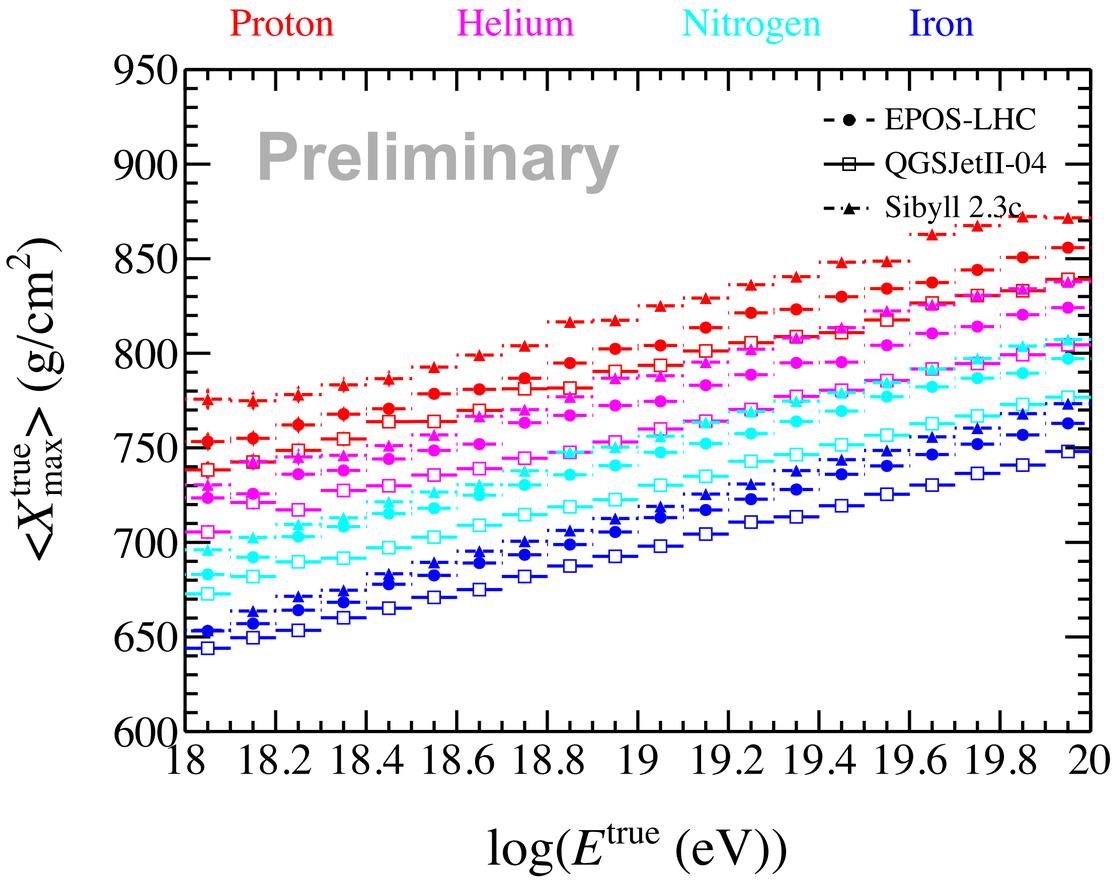
True

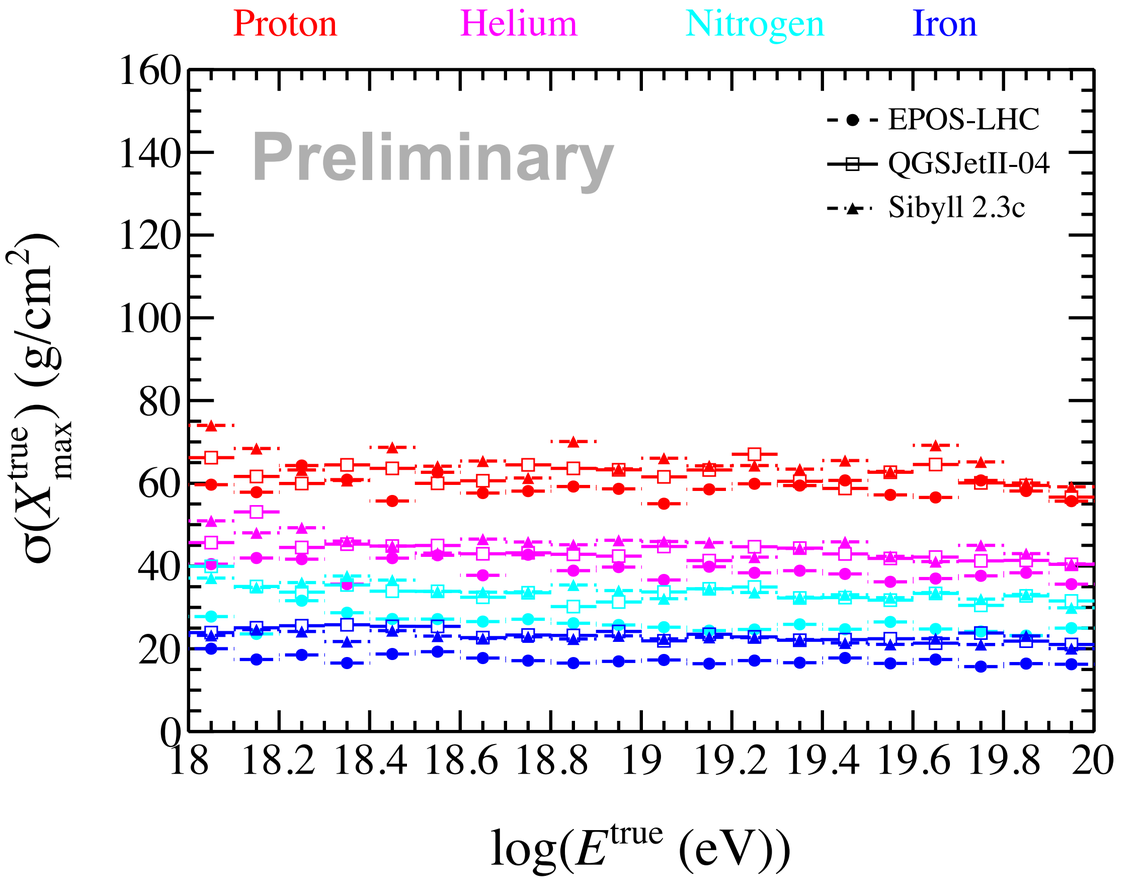


Reconstructed

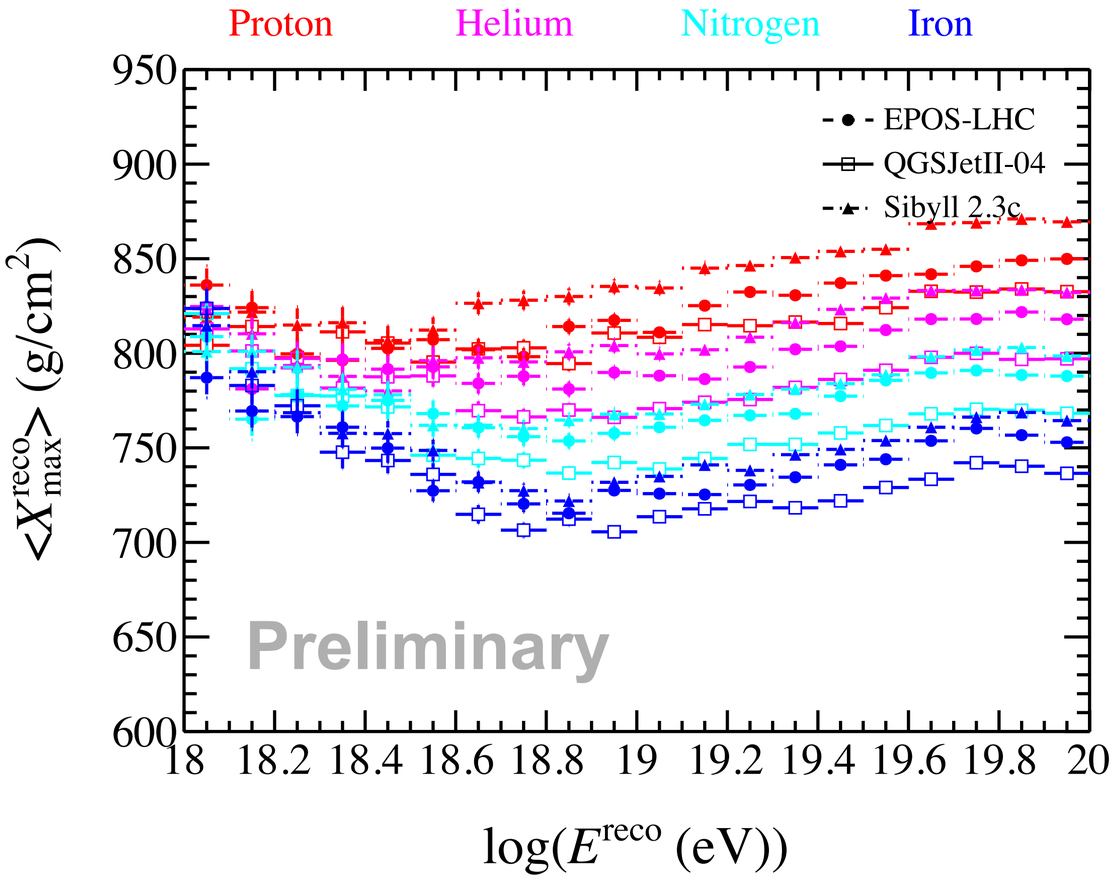


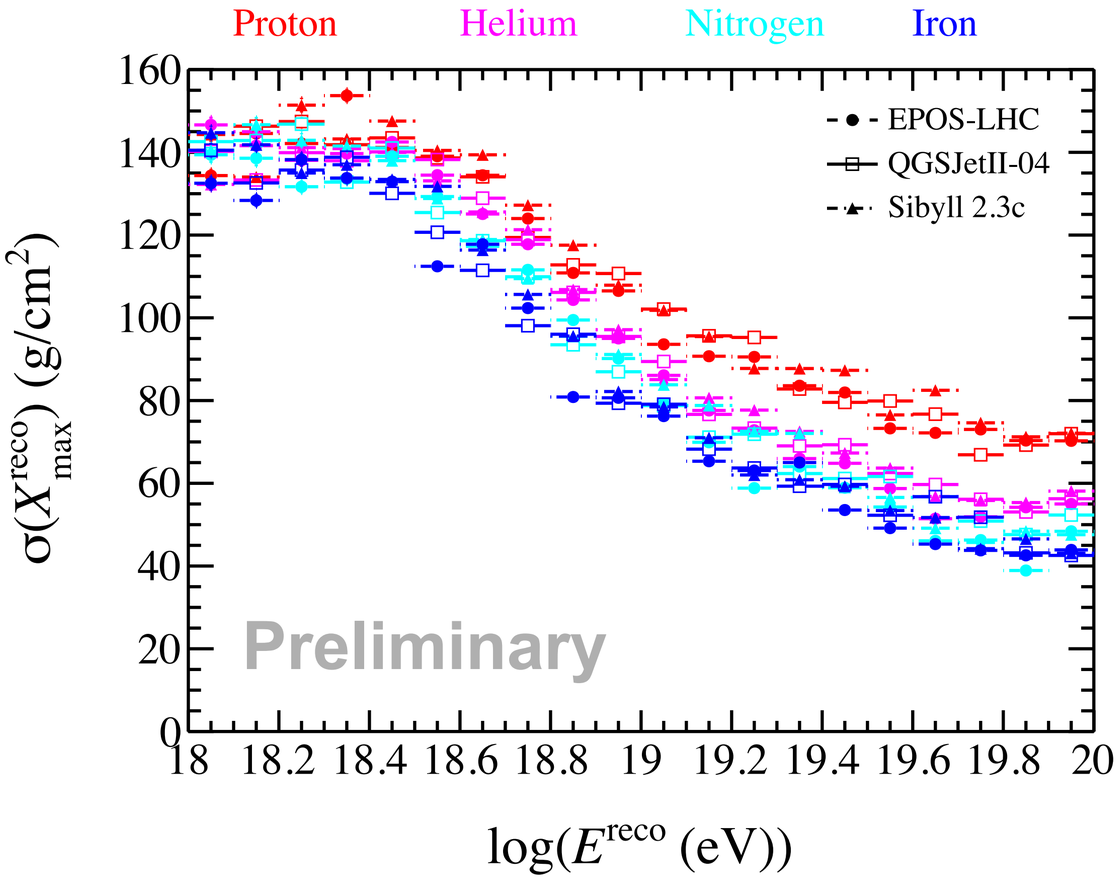
True X_{max} rails





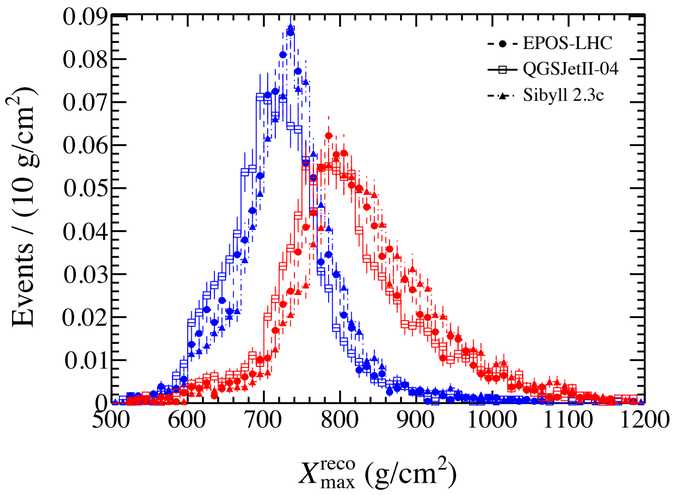
Reconstructed X_{max} rails



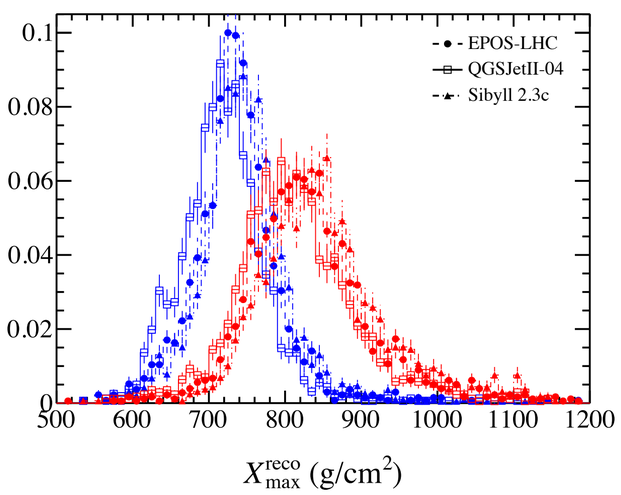


Reconstructed X_{max} distributions

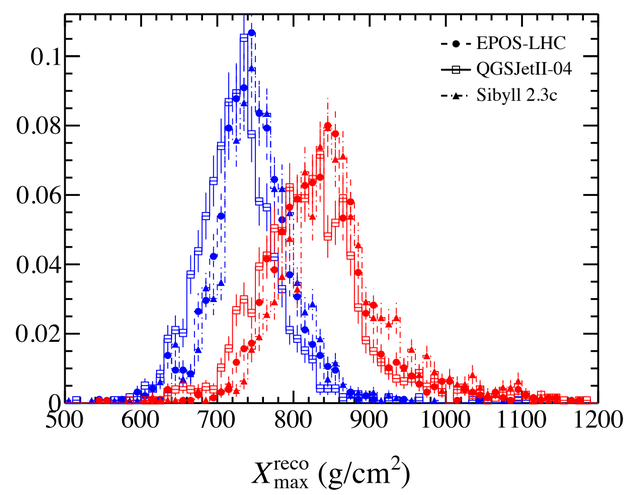
10 - 20 EeV



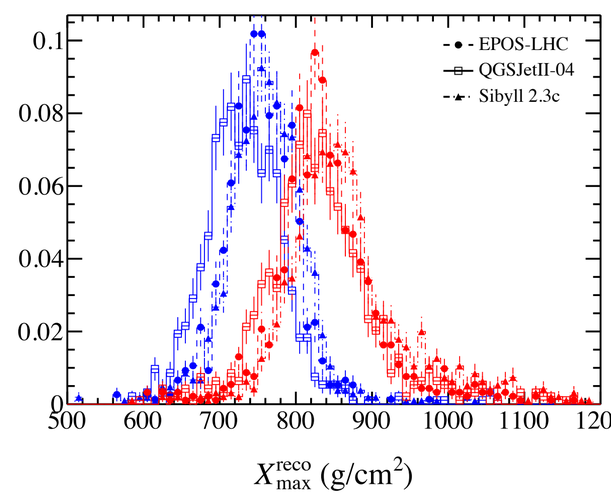
20 - 30 EeV



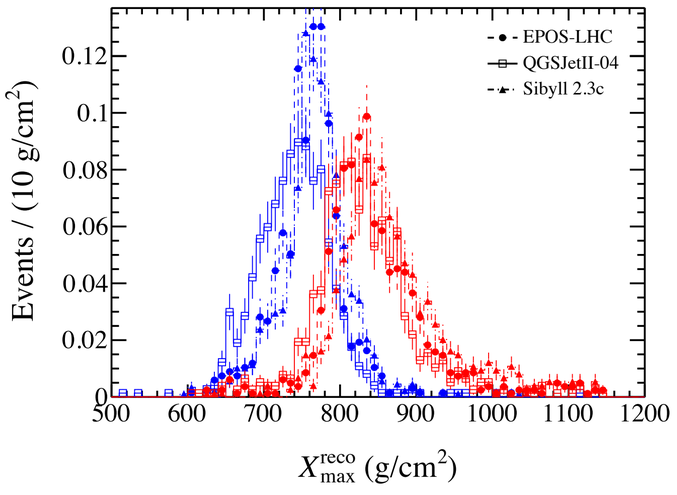
30 - 40 EeV



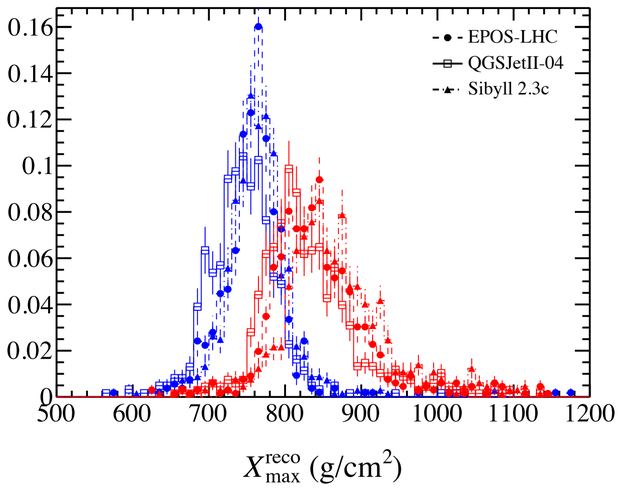
40 - 50 EeV



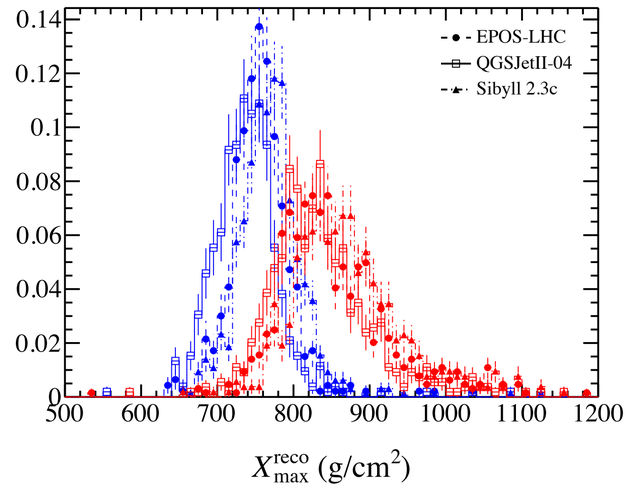
50 - 60 EeV



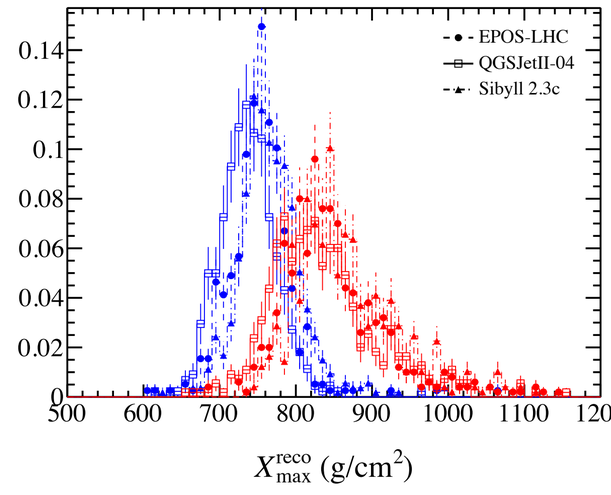
60 - 70 EeV



70 - 80 EeV



80 - 90 EeV



A lot of remaining works to optimize quality cuts, neural network algorithms...

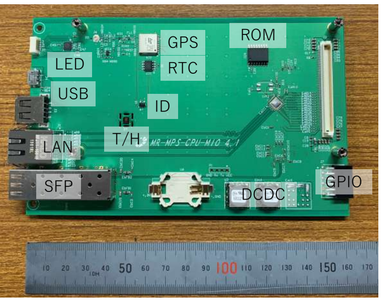
Electronics and PMT calibration in laboratory

EAST
Fluorescence detector Array of Single-pixel Telescopes

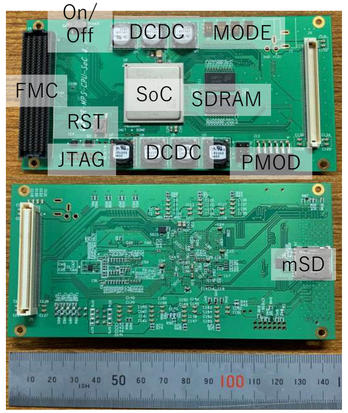
New electronics development

Dual 32ch FADC (ADS52J90), 64ch FADC at maximum
14bit 32.5 MSPS 32ch

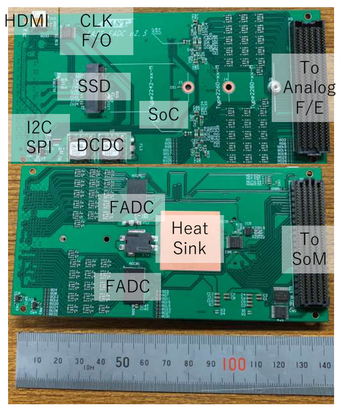
MIO



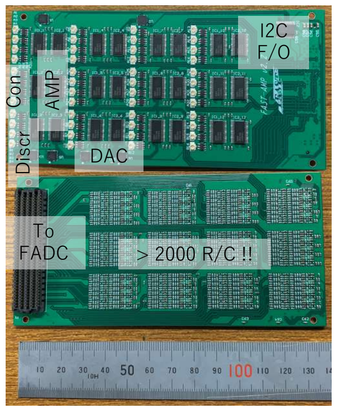
SoC



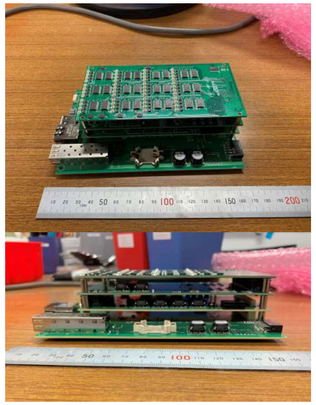
FADC



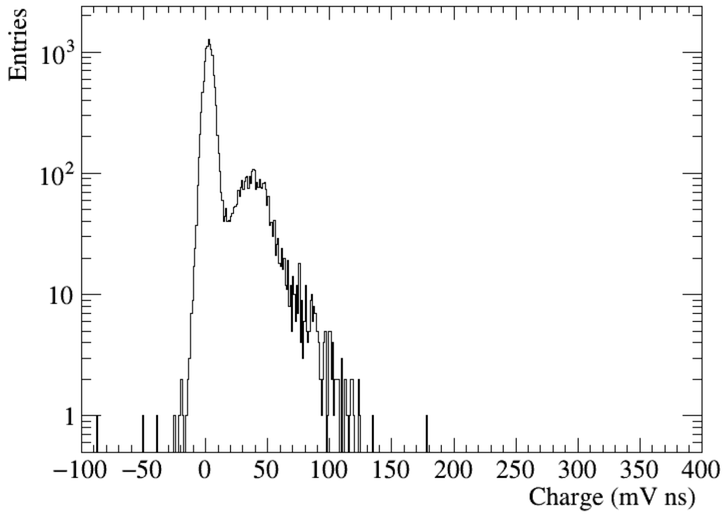
AMP



Assembly

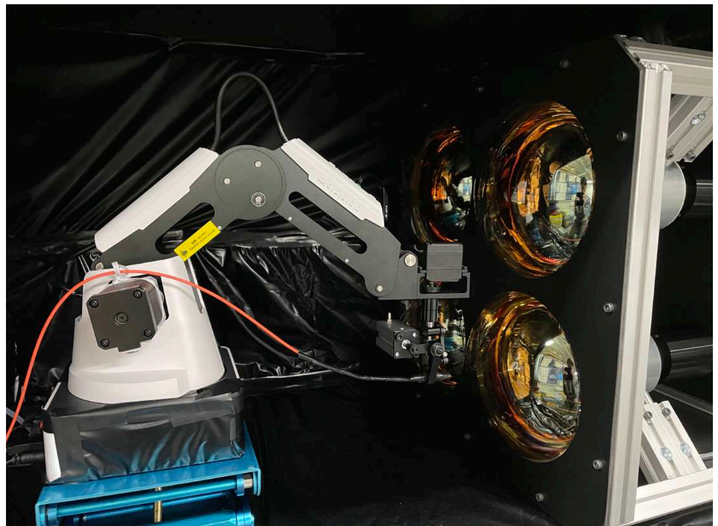


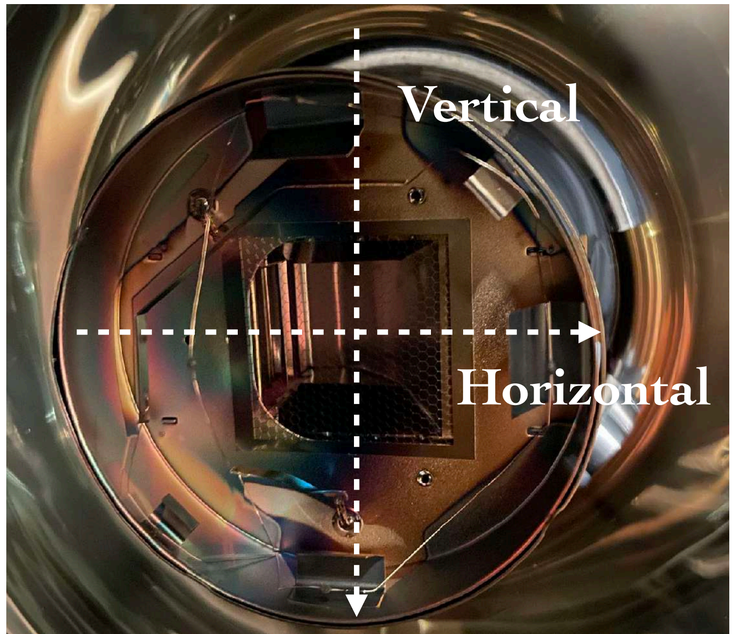
Single Photo Electron



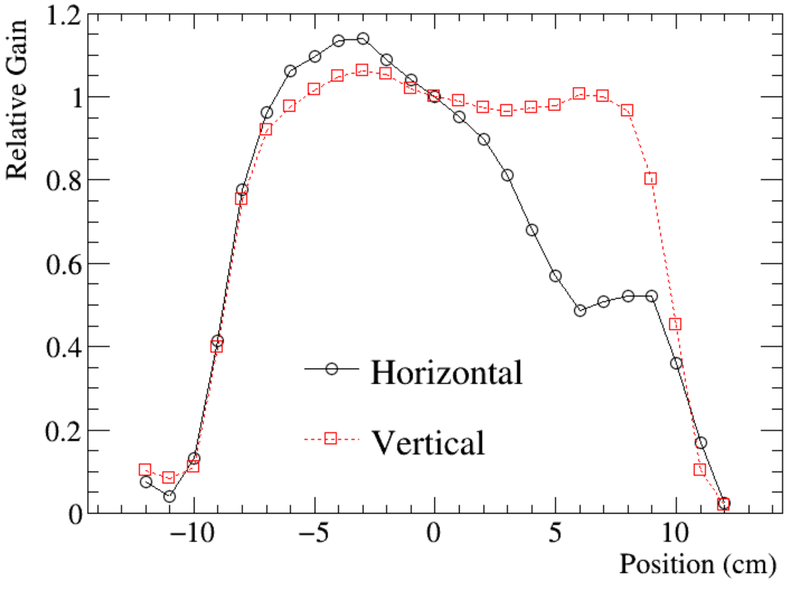
Calibration using Robot arm

(0.2 mm accuracy)





Non-uniformity

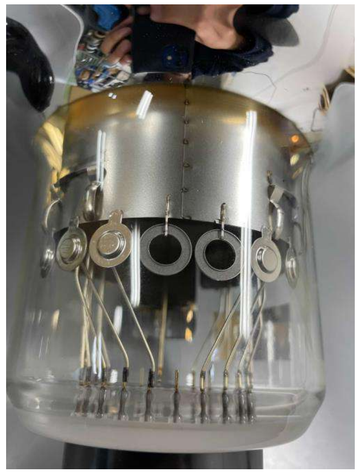


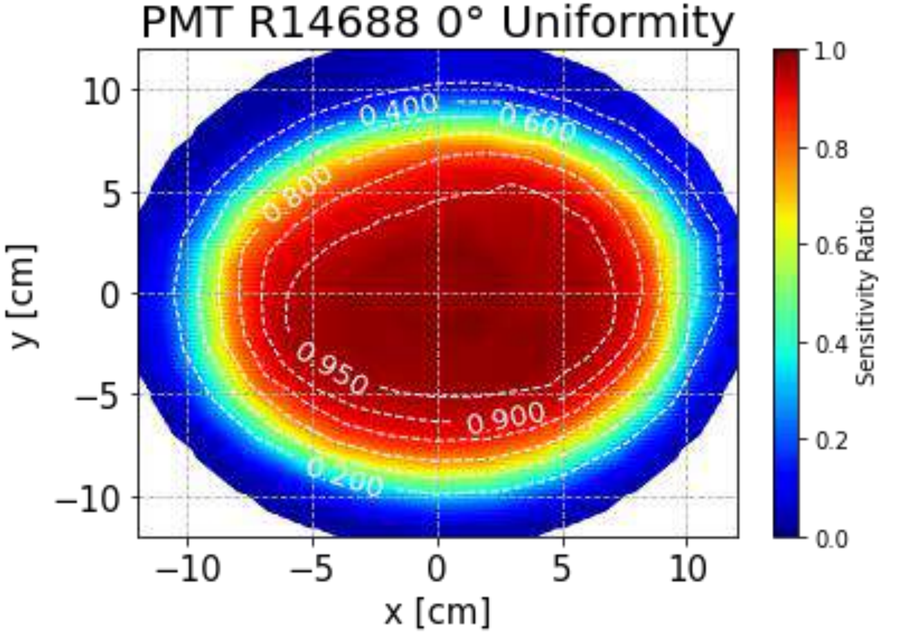
New PMT being developed to reduce non-uniformity

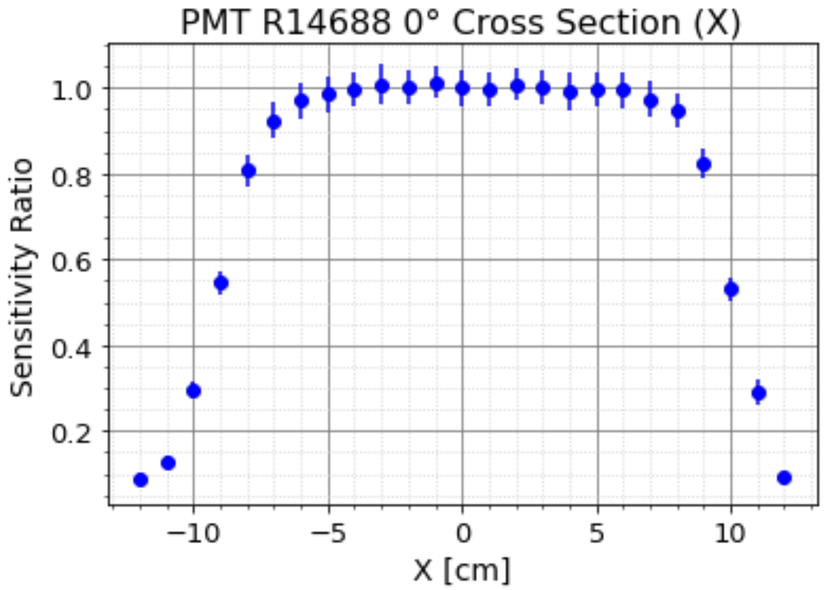
Fluorescence detector Array of Single-pixel Telescopes

Work: Hiromu Nagasawa

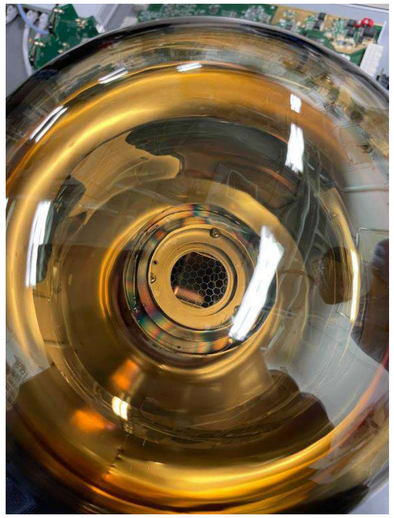
PMT R14688



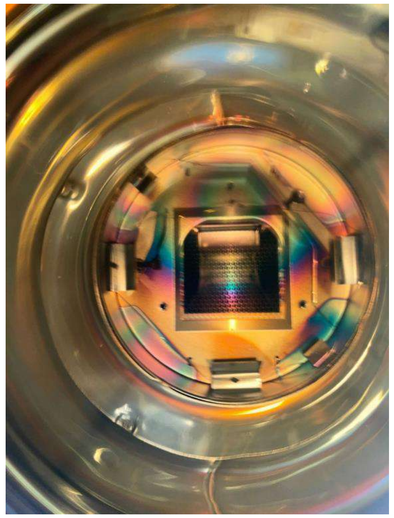




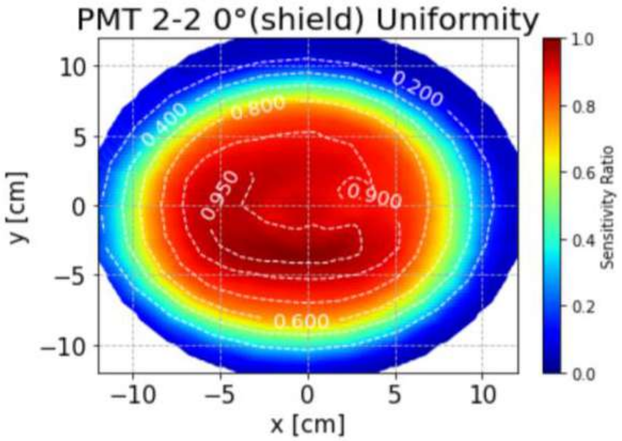
←↓ R14688

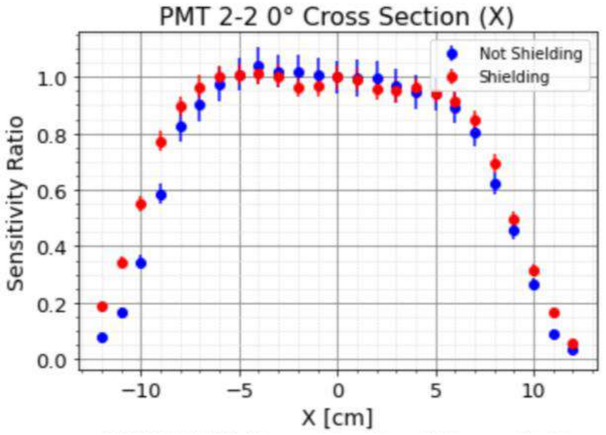


↓ R5912-03

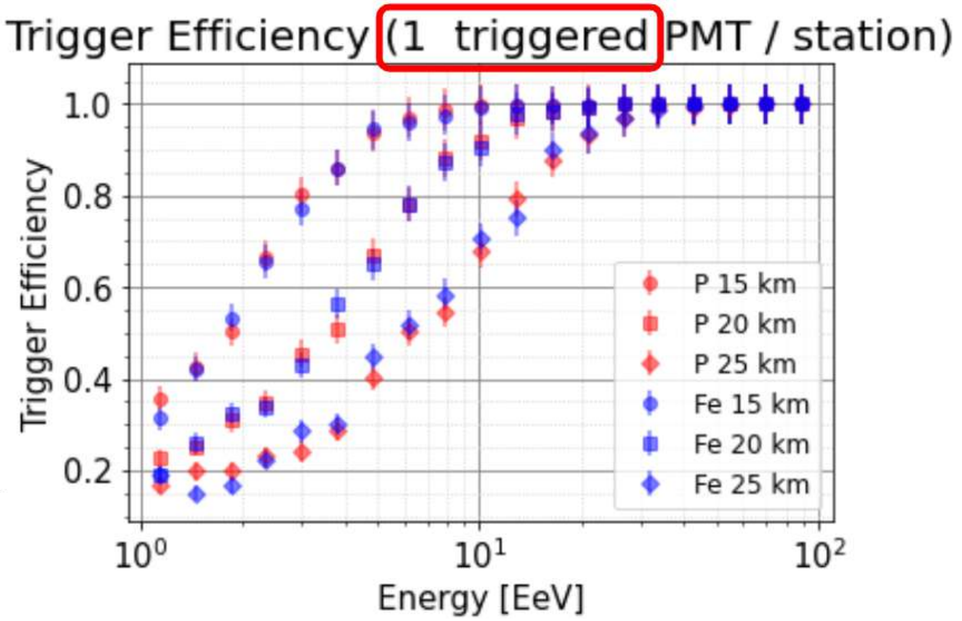


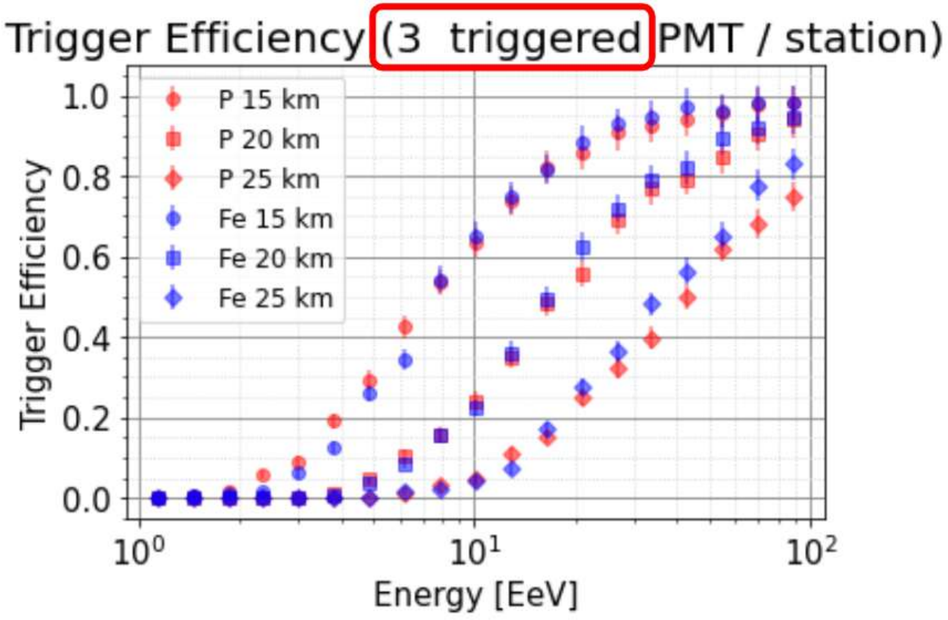
R5912-03, with magnetic shied (FINEMET)

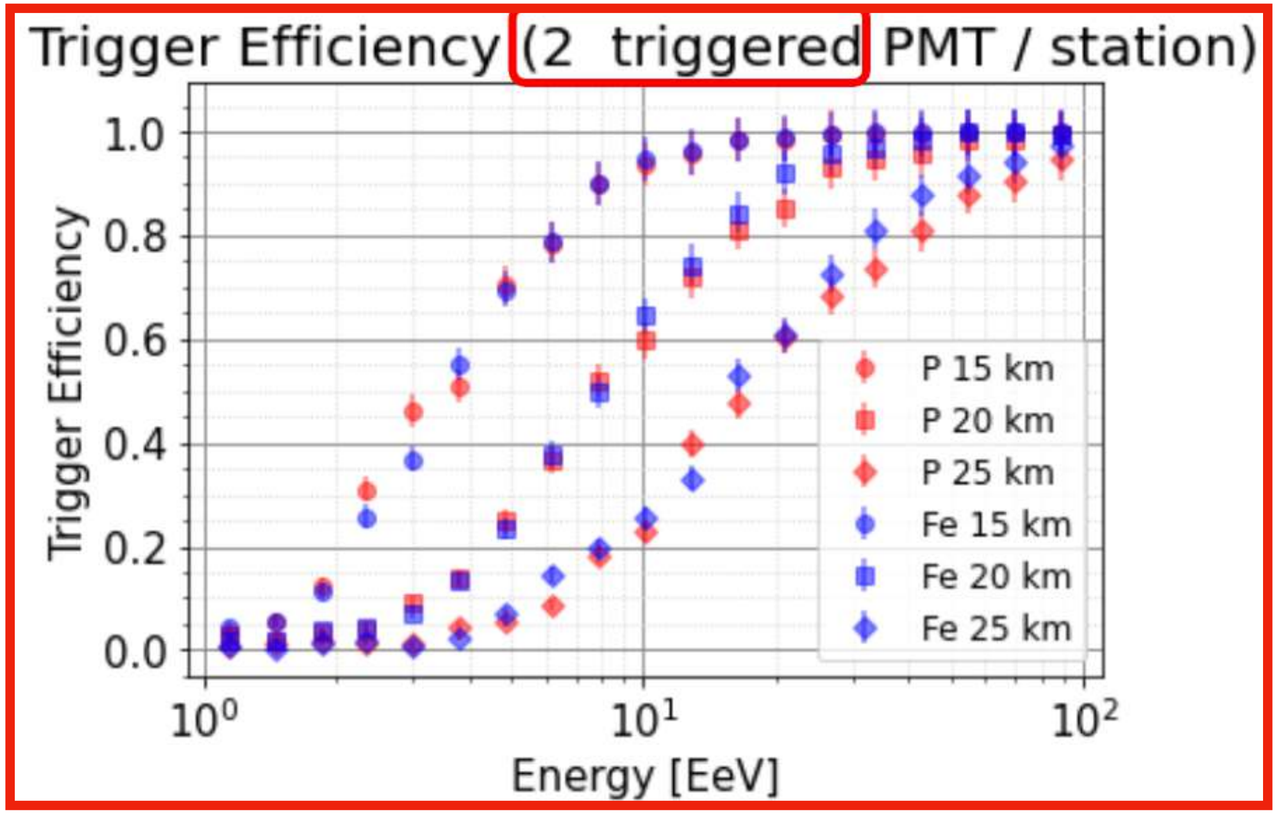




Trigger algorithm and spacing optimization





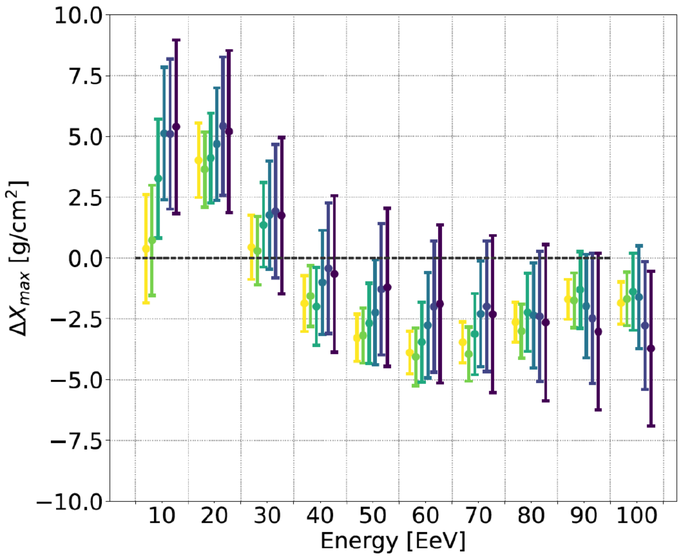


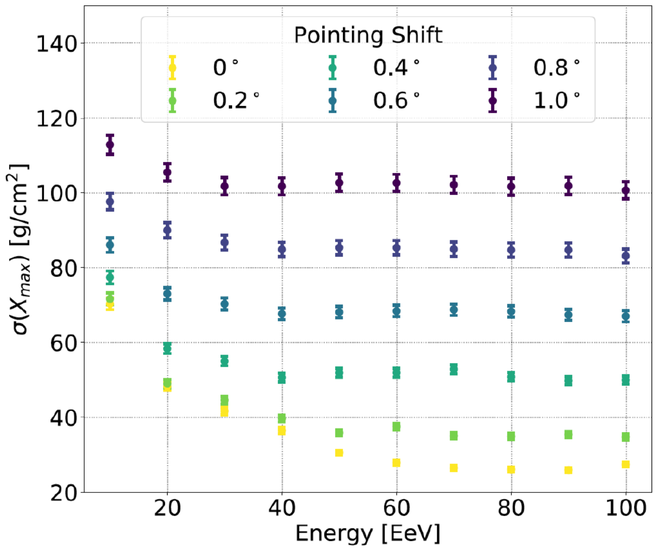
- 20 km spacing is suitable
- Two adjacent PMTs triggered within 12.8 μs
- Time window : 51.8 μs

Pointing calibration by flying light source

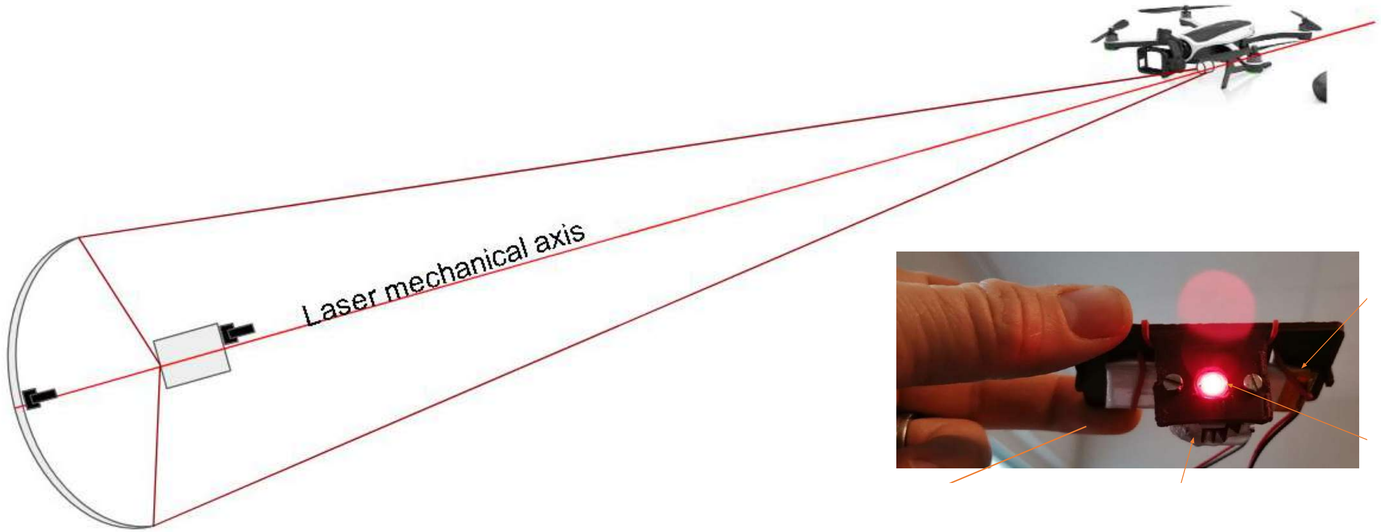
Importance of telescope pointing

Work: Justin Albury

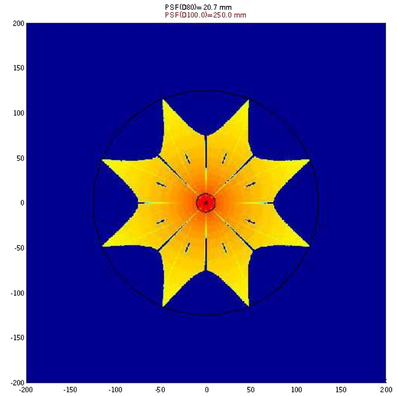


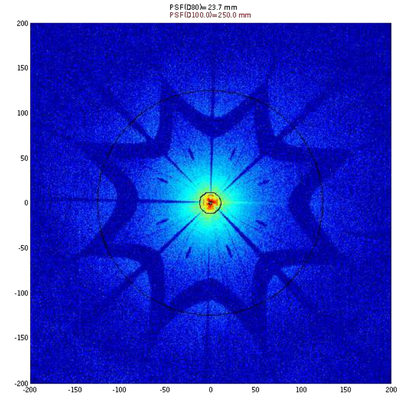


Work: Dusan Mandat, Miroslav Pech, Ladislav Chytka



Test flight at Czech republic



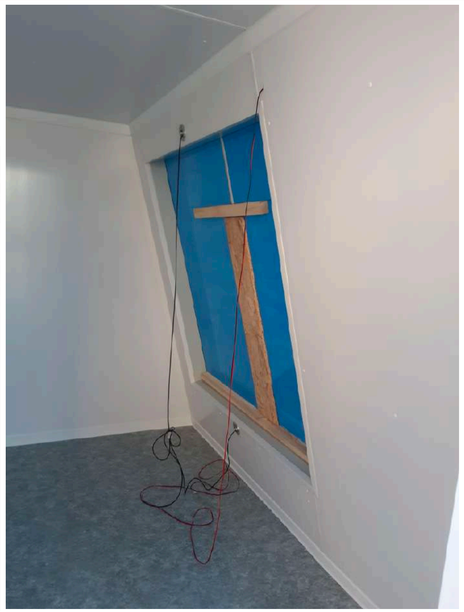


Simulation

Measurement

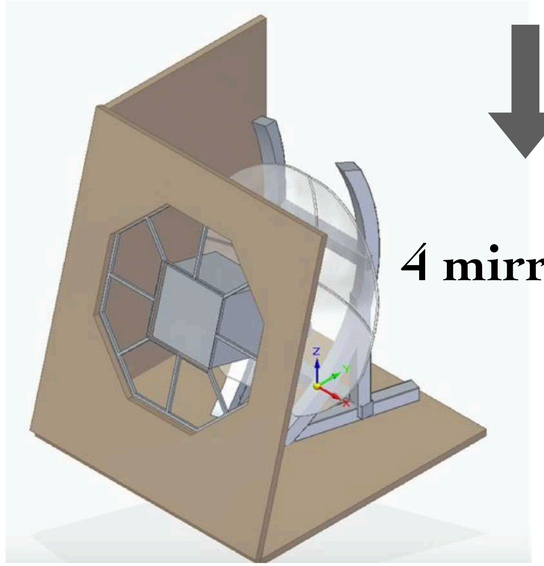
FAST design for stand-alone field measurement

Fluorescence detector Array of Single-pixel Telescopes

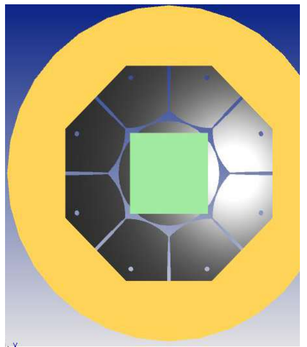


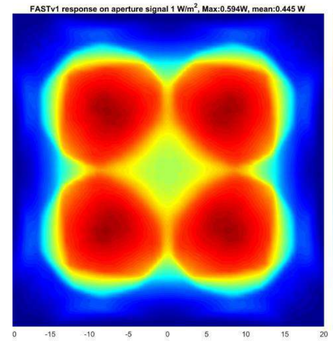
Optimization of optics using 4 mirrors

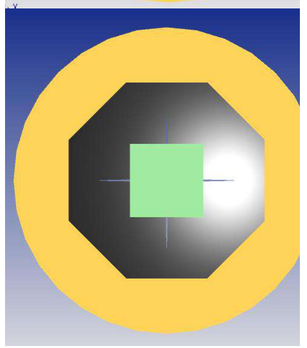
9 mirrors

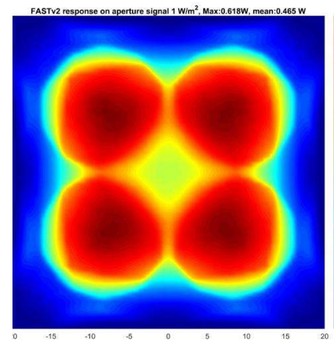


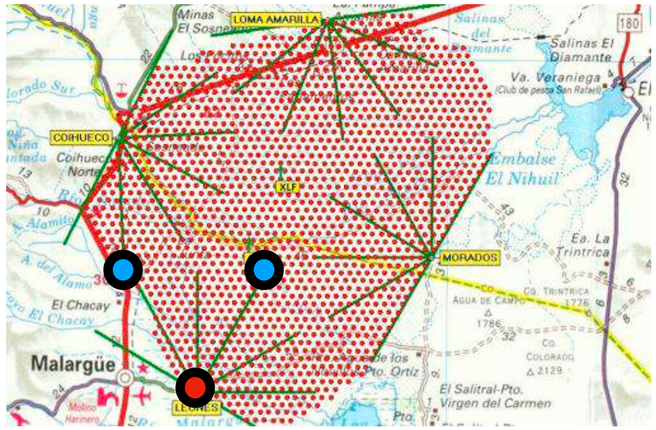
4 mirrors











- 2 telescopes at each station at the distance of 20 km
  - 30 deg x 60 deg field of view
- Need to start a consideration of possible installed location

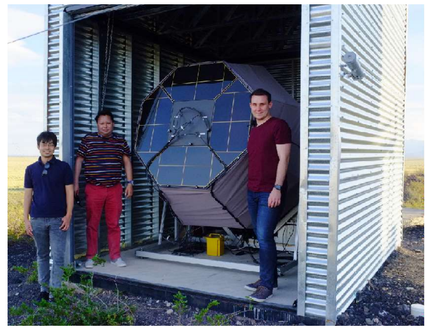
FAST
Fluorescence detector Array of Single-pixel Telescopes

Summary and future plan

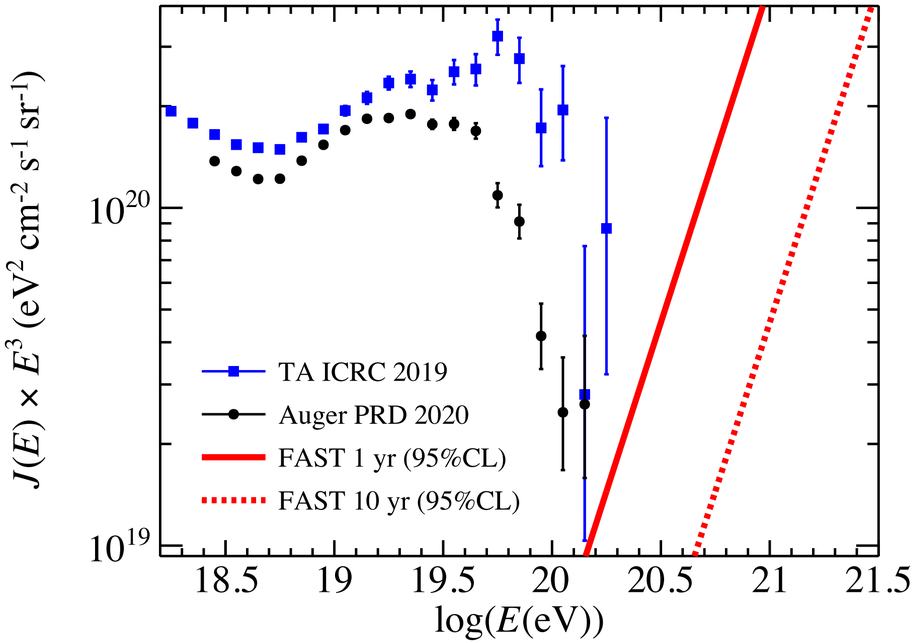
- **Fluorescence detector Array of Single-pixel Telescopes (FAST)**
  - Low-cost fluorescence telescope array
  - Promising concept as next-generation cosmic ray observatory to fulfill requirements
  - Anisotropy with mass composition sensitivity
- **Preliminary performance estimation using neural network first guess reconstruction**
  - Preliminary resolution of neural network reconstruction at **40 EeV**
    - Arrival direction: 4.2 deg, Core: 465 m
    - Energy: 8%, Xmax: 30 g/cm^2 ($\Delta \ln A \sim 1$)
- **Next step and challenges**
  - Stand-alone operation of FAST "array" in field

FAST@TA

FAST@Auger



Expected sensitivity with a full-size FAST array



https://www.fast-project.org