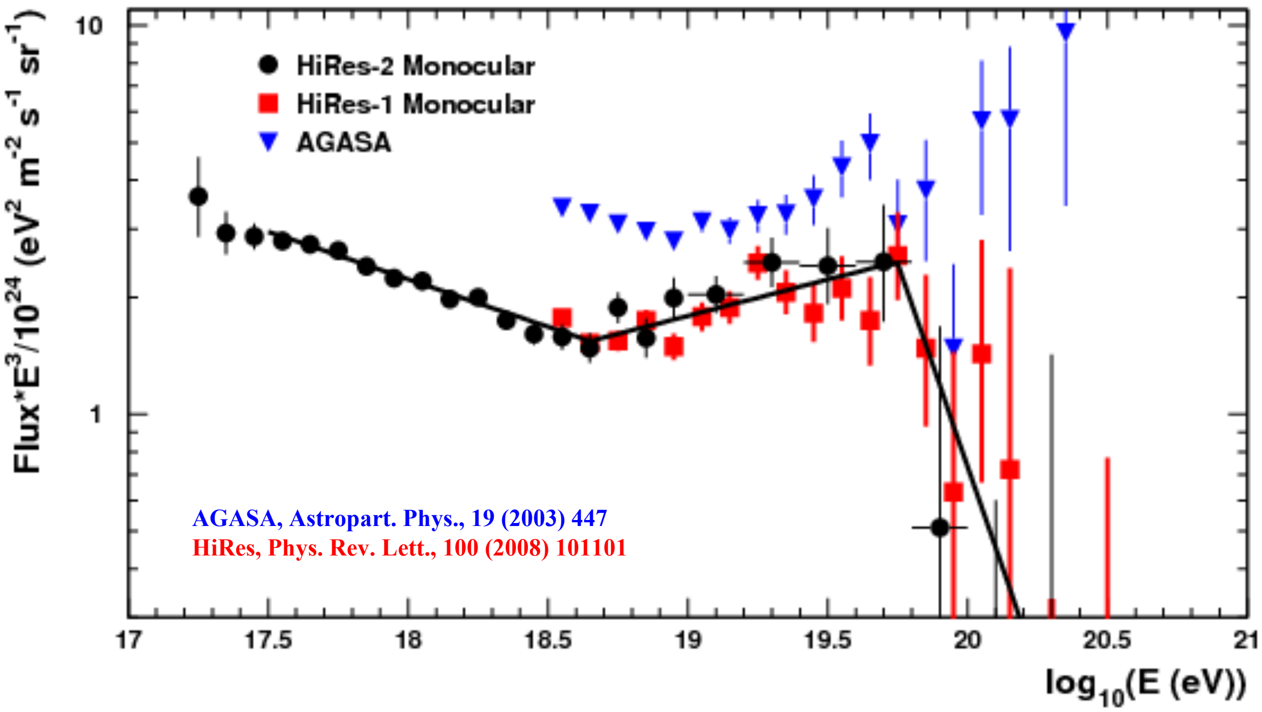
On the challenging problem to estimate the energy of the Ultra High Energy Cosmic Rays

V. Verzi
INFN, Roma "Tor Vergata"

EARLY 2000s

AGASA

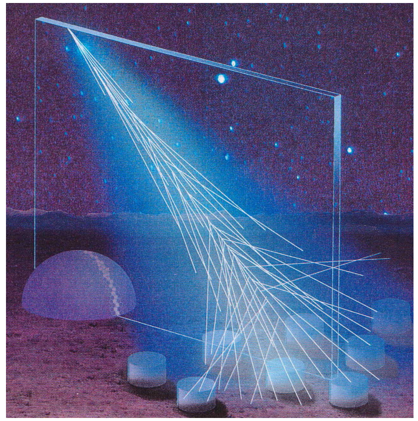
- absence of the GZK effect ?   Exotic particles ?
- low statistics and wrong energy scale



unc. in the flux ≈ (γ-1) ΔE/E

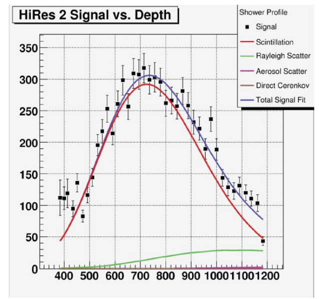
at 10^{20} eV   √s~ 400 TeV

FD



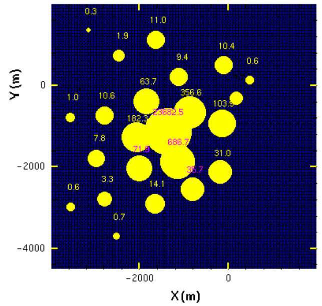
SD

HiRes
Fluorescence Detector



calorimetric energy

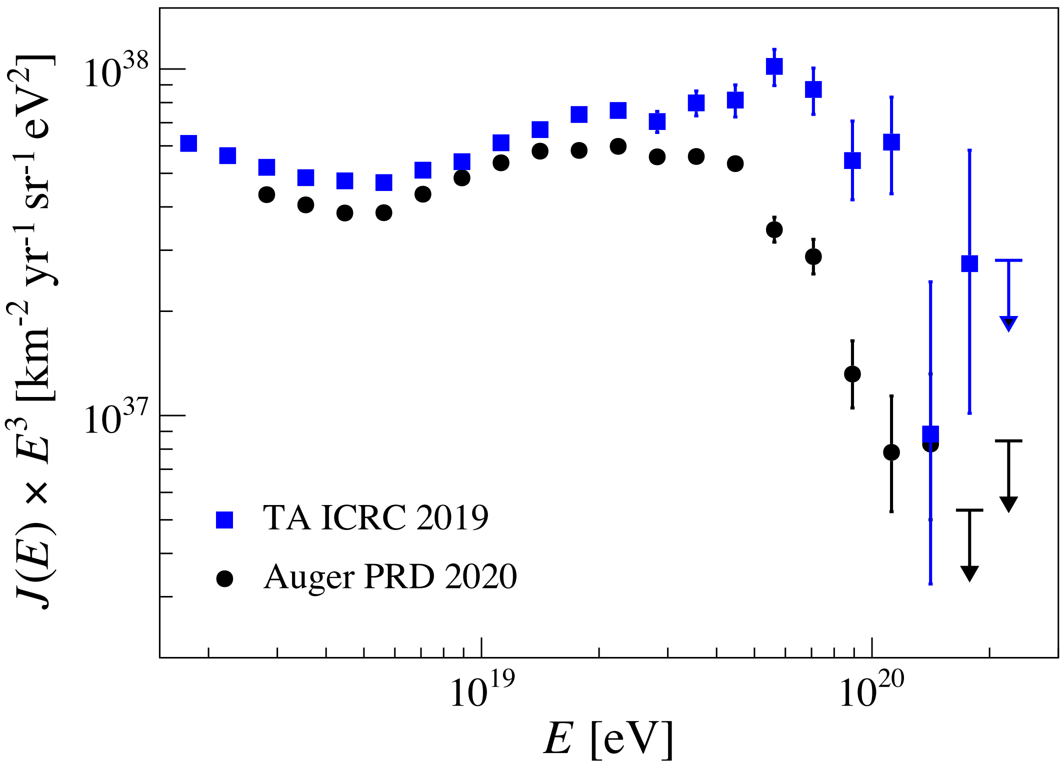
AGASA
Surface Detector

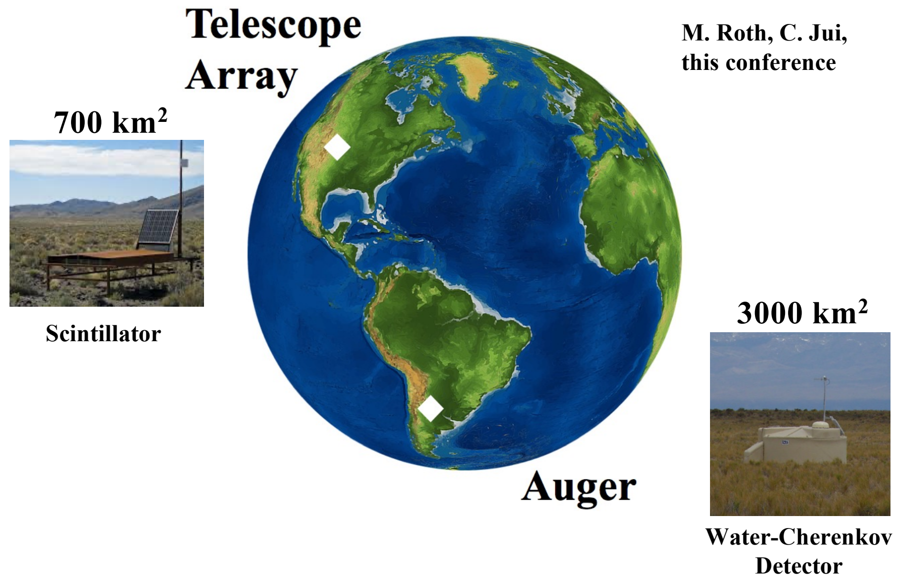


energy from simulations

hadronic interactions ?
primary mass ?

MODERN HYBRID OBSERVATORIES





Hybrid detectors (SD+FD)
calibrate the SD signals against FD energies

- ➢ 100% duty cycle (SD)
- ➢ calorimetric estimate of E (FD)

- **significantly better situation but still some tension at the cut-off**
- **uncertainty in the energy scale (15%-20%) still dominating the one in the flux**

MODERN HYBRID OBSERVATORIES

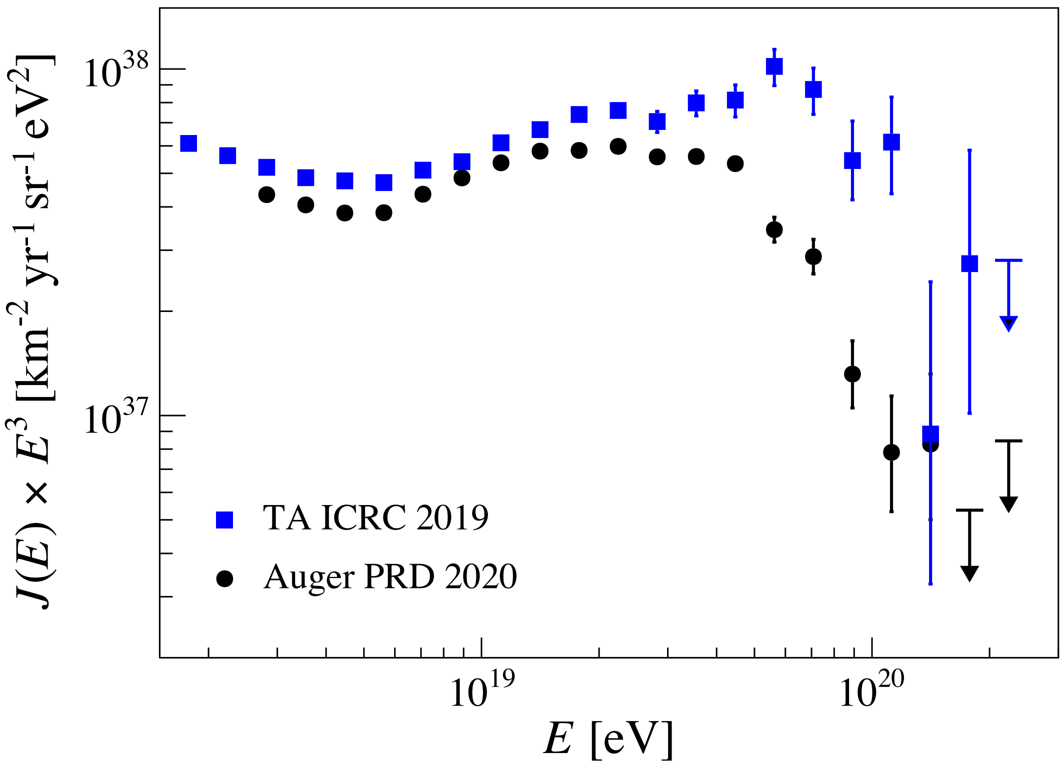
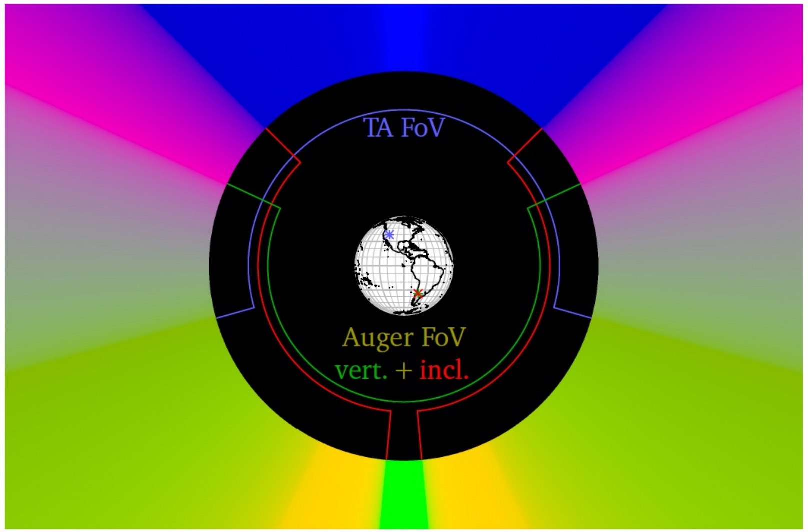


figure from A. Di Matteo, COST 2023



- understanding of the differences important to combine the Auger and TA data (full sky coverage)
- joint Working Groups Auger-TA to combine the data

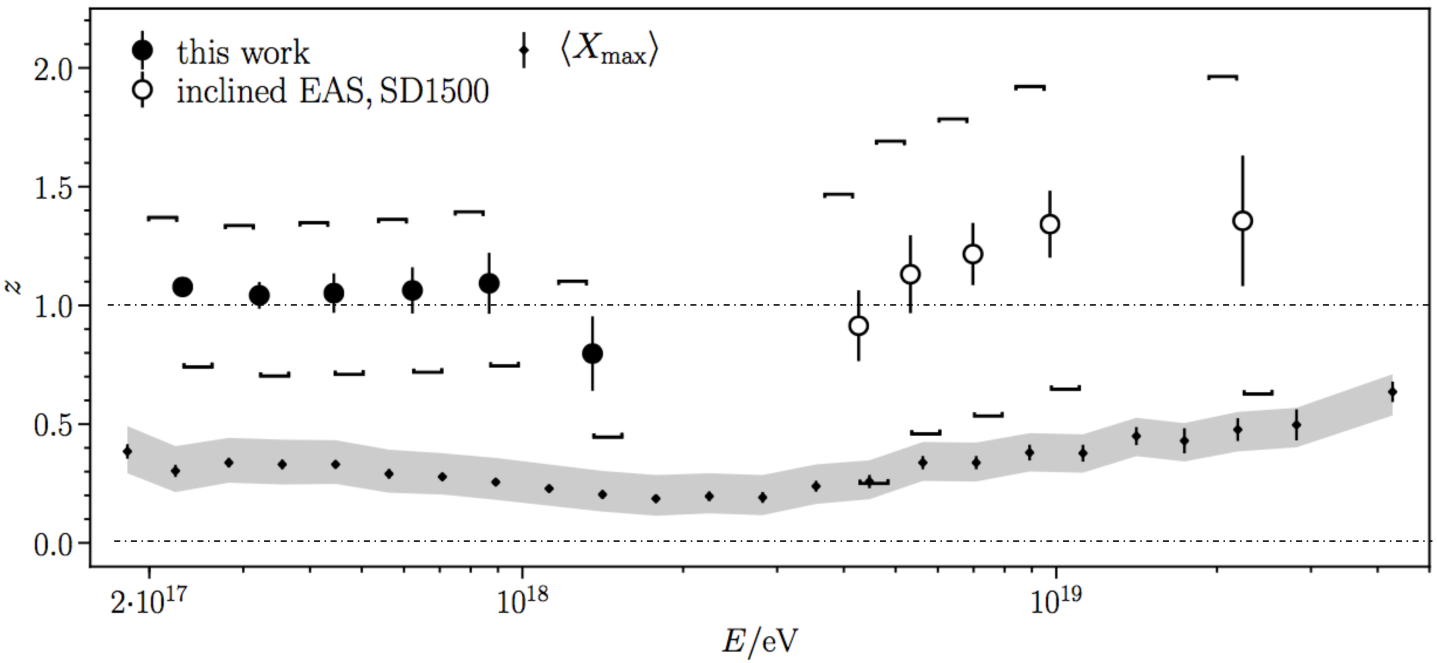
MUON NUMBER EXCESS

Interpretation of N_μ very sensitive to the energy scale

$N_\mu \sim E^{\beta}$

$\beta \approx 0{,}9$

UMD $\quad$ N_μ **excess** $\quad$ **SD θ>60^0**



Fe

p

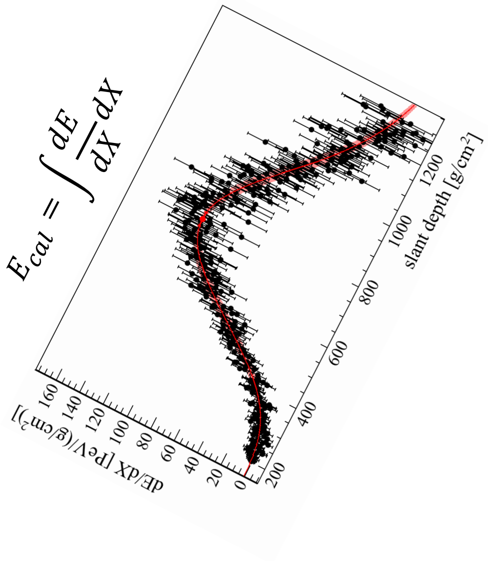
Auger,
Eur. Phys. J. C (2020) 80

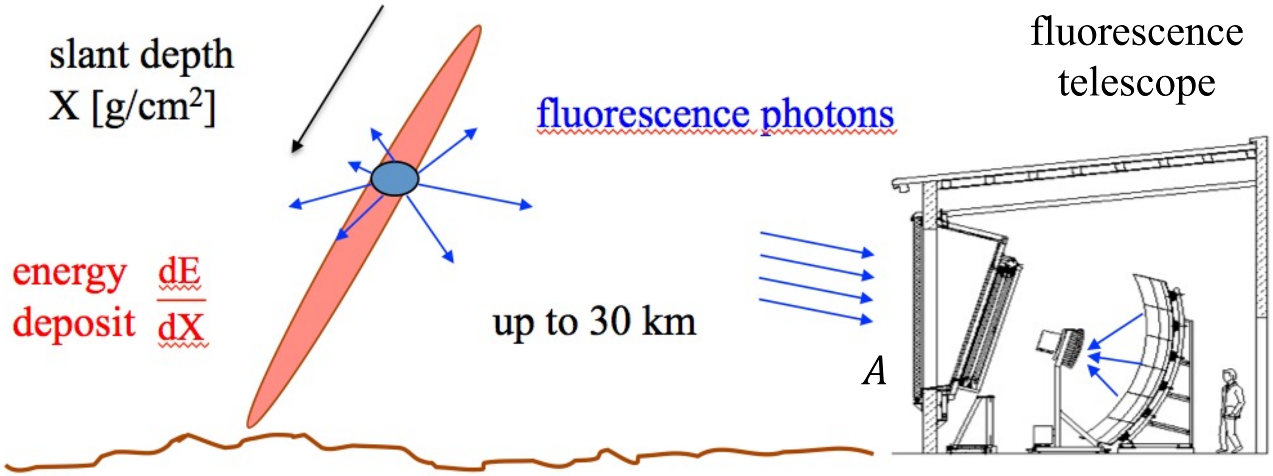
$$z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_{\mu,\mathrm{p}}^{\mathrm{det}})}{\ln(N_{\mu,\mathrm{Fe}}^{\mathrm{det}}) - \ln(N_{\mu,\mathrm{p}}^{\mathrm{det}})}$$

$z = 0$: proton, $z = 1$: iron

N_μ excess observed by Auger likely due to the hadronic interaction models

FLUORESCENCE DETECTION TECHNIQUE





fluorescence photons emitted from the de-excitation of the atmospheric nitrogen (N_2 excited by δ rays)

$$n_{ADC} \sim \frac{dE}{dX} Y_{fluo} \frac{A}{r^2} T_{atm} C_{calib}$$

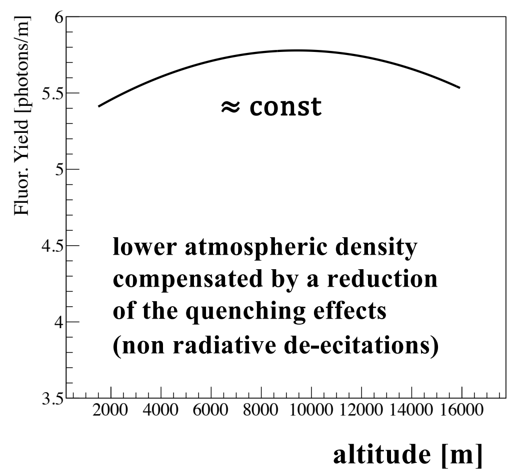
number of photons ∝ dE/dX

fluorescence yield

isotropic emission

atmospheric attenuation

telescope calibration



ABSOLUTE FLUORESCENCE YIELD

measured in lab

nowadays measured with a <4% uncertainty (AIRFLY)

emission process well understood but too large uncertainty in the theoretical prediction

grey points - old measurements affected by a known bias:

some δ rays escape the detector f.o.v. → underestimation of Y_{337}

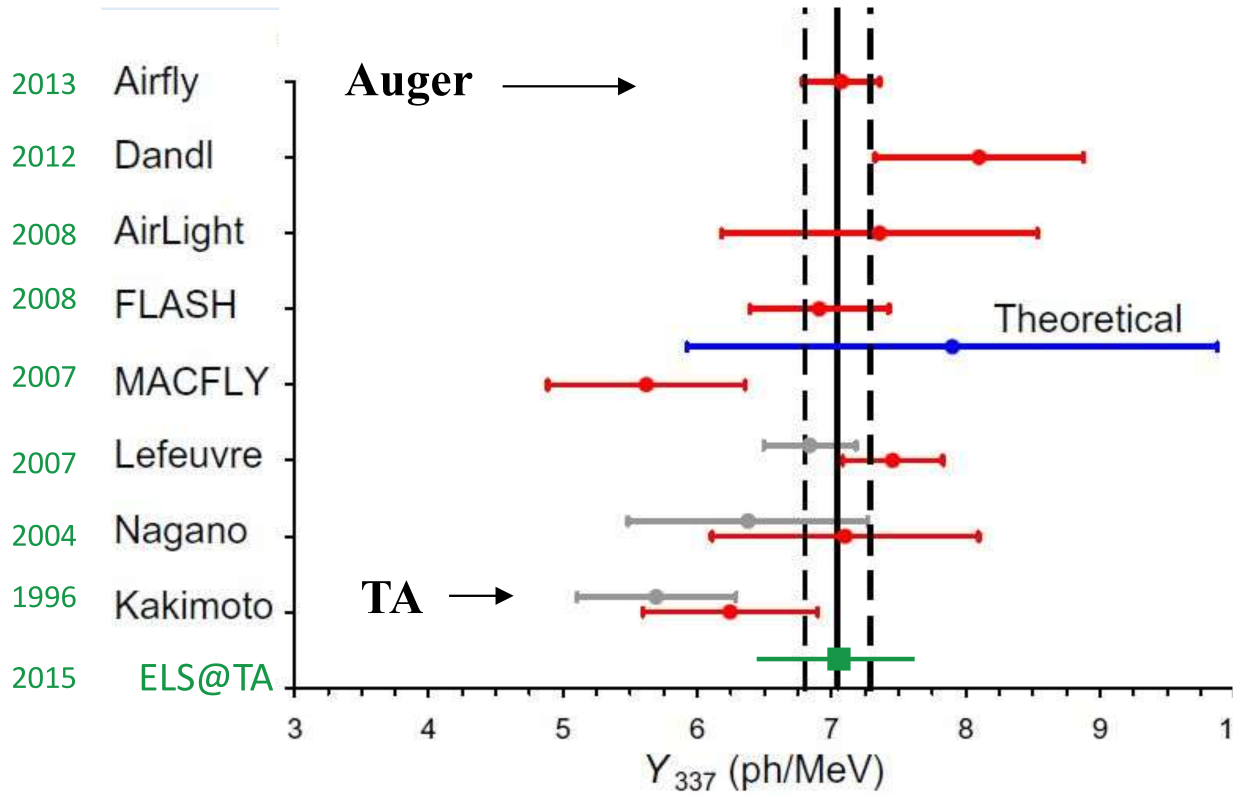


figure from J. Rosado, F. Blanco and F. Arqueros, ApP 55(2014) 51-62
ELS@TA added by M. Fukushima, GCOS workshop 2022

AIRFLY

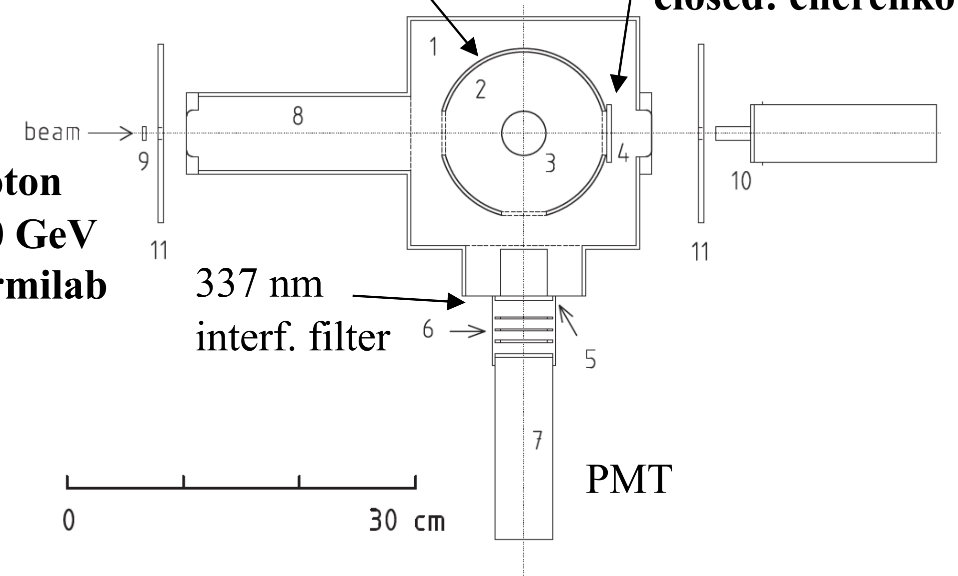
Absolute Yield (337 nm)

Astropart. Phys. 42 (2013) 90

precise measurement by normalizing to a well know process (avoid absolute PMT calibration)

$$Y_{fluo} \sim Y_{cher} \frac{N_{fluo}}{N_{cher}}$$

exit port
opened: fluorescence
closed: cherenkov

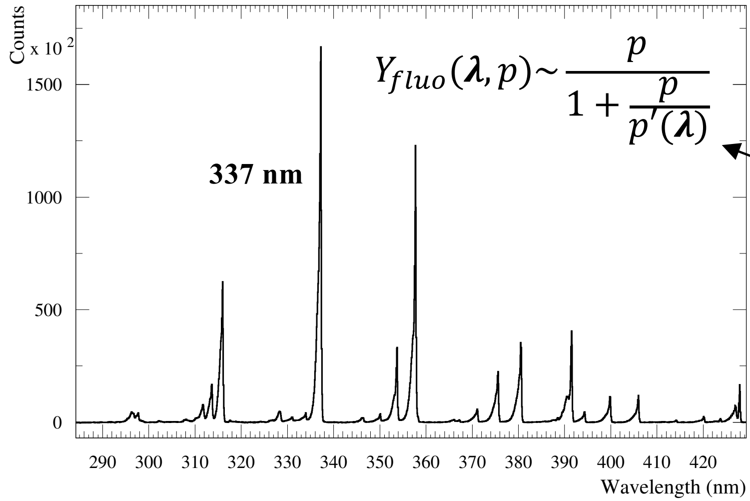


proton
120 GeV
Fermilab

Wavelength spectrum and quenching effects

Astropart. Phys. 28 (2007) 41

relative measurements



$$Y_{fluo}(\lambda, p) \sim \frac{p}{1 + \frac{p}{p'(\lambda)}}$$

$$p'(\lambda) \propto \frac{\sqrt{T}}{\sigma}$$

0,1 nm resolution

AWA and VdG (Argonne)
- **spectrum**
- **dependence on pressure, humidity and temperature**

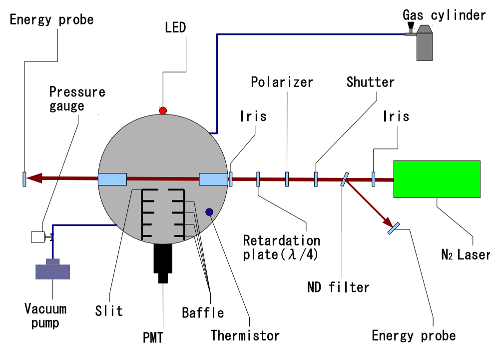
uncertainty in shower energy from FY < 4%

ABSOLUTE TELESCOPE CALIBRATION

Auger: calibrate the full telescope illuminating uniformly the camera with a calibrated source

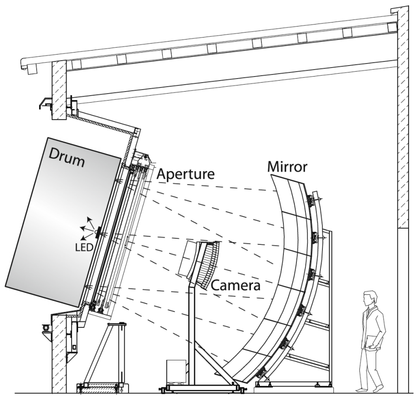
TA: 'piece to piece' calibration. Absolute PMT calibration with Rayleigh scattered light from nitrogen laser

TA CRAYS



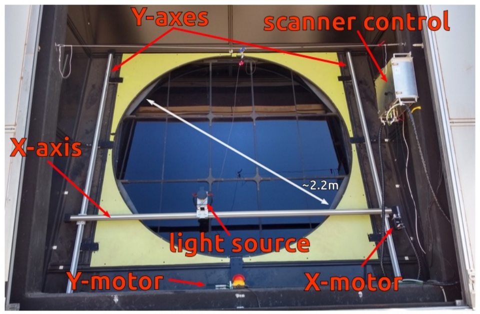
S. Kawana et al., Nucl. Instrum. Meth. A 681 (2012) 68

AUGER DRUM



J. T. Brack et al., JINST 8 (2013) P05014

AUGER X-Y SCANNER

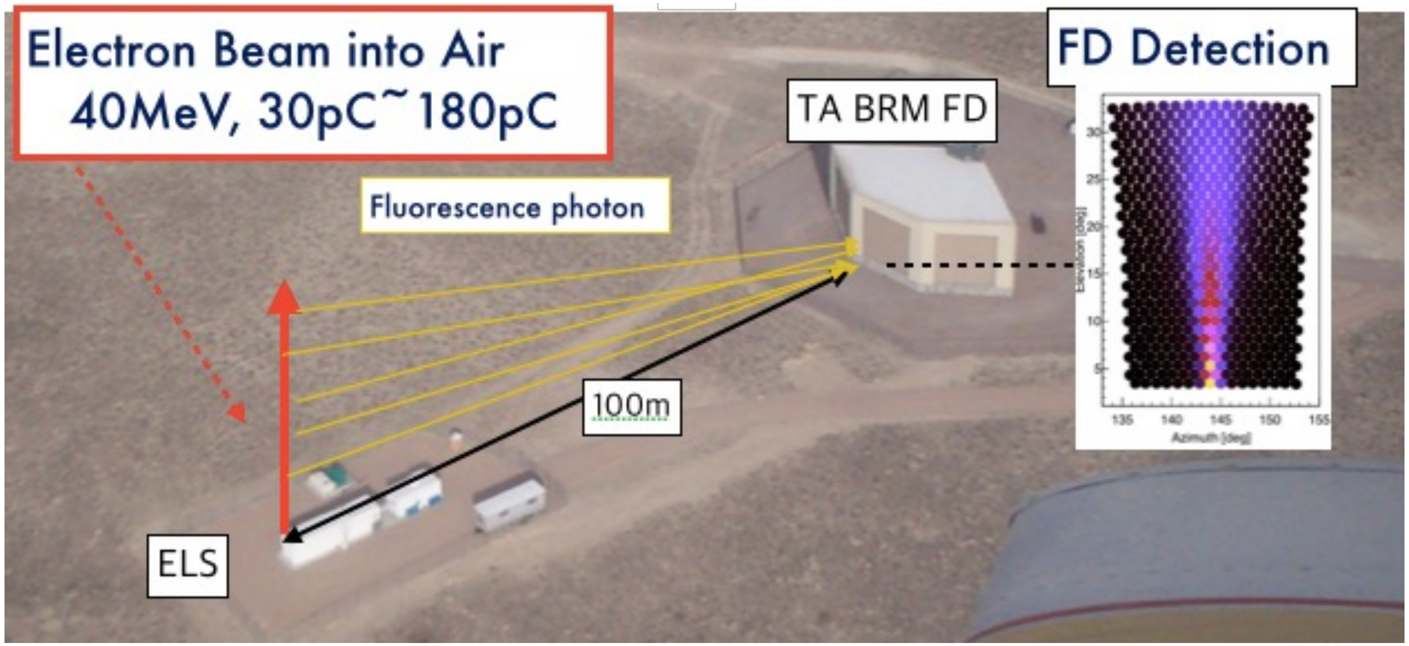


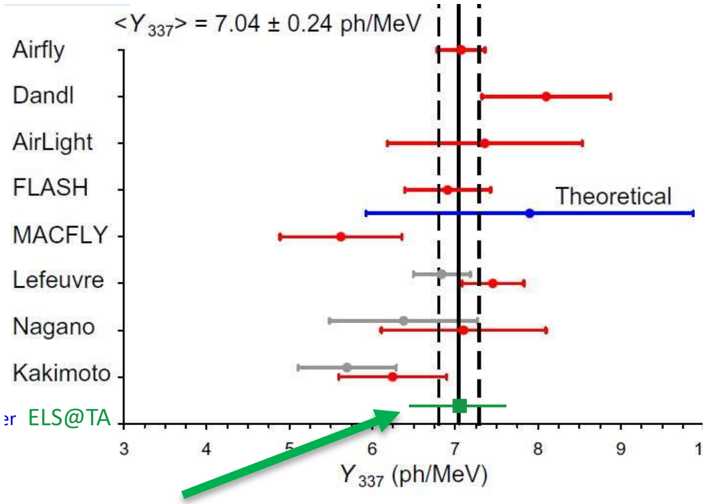
Christoph M. Schäfer PoS (ICRC2023) 305

uncertainty in shower energy from absolute telescope calibration ~ 10%

LINAC ACCELERATOR AT THE TA SITE

B. Shin et al., PoS (ICRC2015) 640



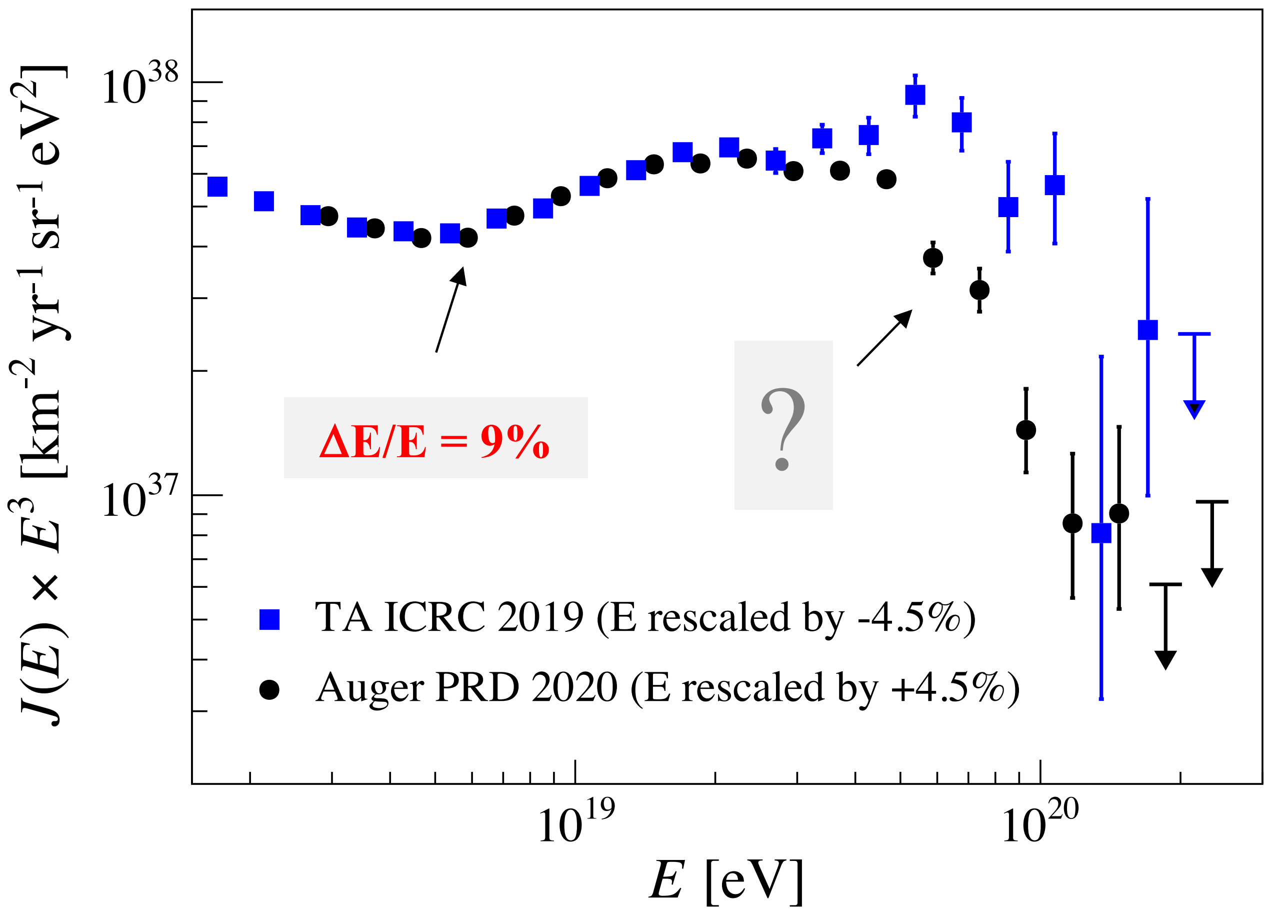


- combined effect of fluorescence yield and telescope absolute calibration
- remarkable agreement with AIRFLY

→ absolute calibration of the TA telescope well under control

ENERGY SCALE: AUGER vs TA

Auger and TA, UHECR 2022, ICRC2023

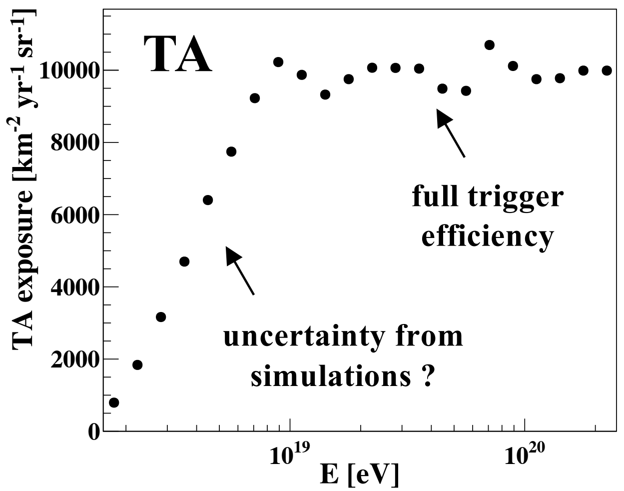


almost a perfect agreement around the ankle using the same fluorescence yield and invisible energy

$$E = E_{cal} + E_{inv} \quad (\nu, \mu, ..)$$

note: Auger E_{inv} from data (N_μ excess)

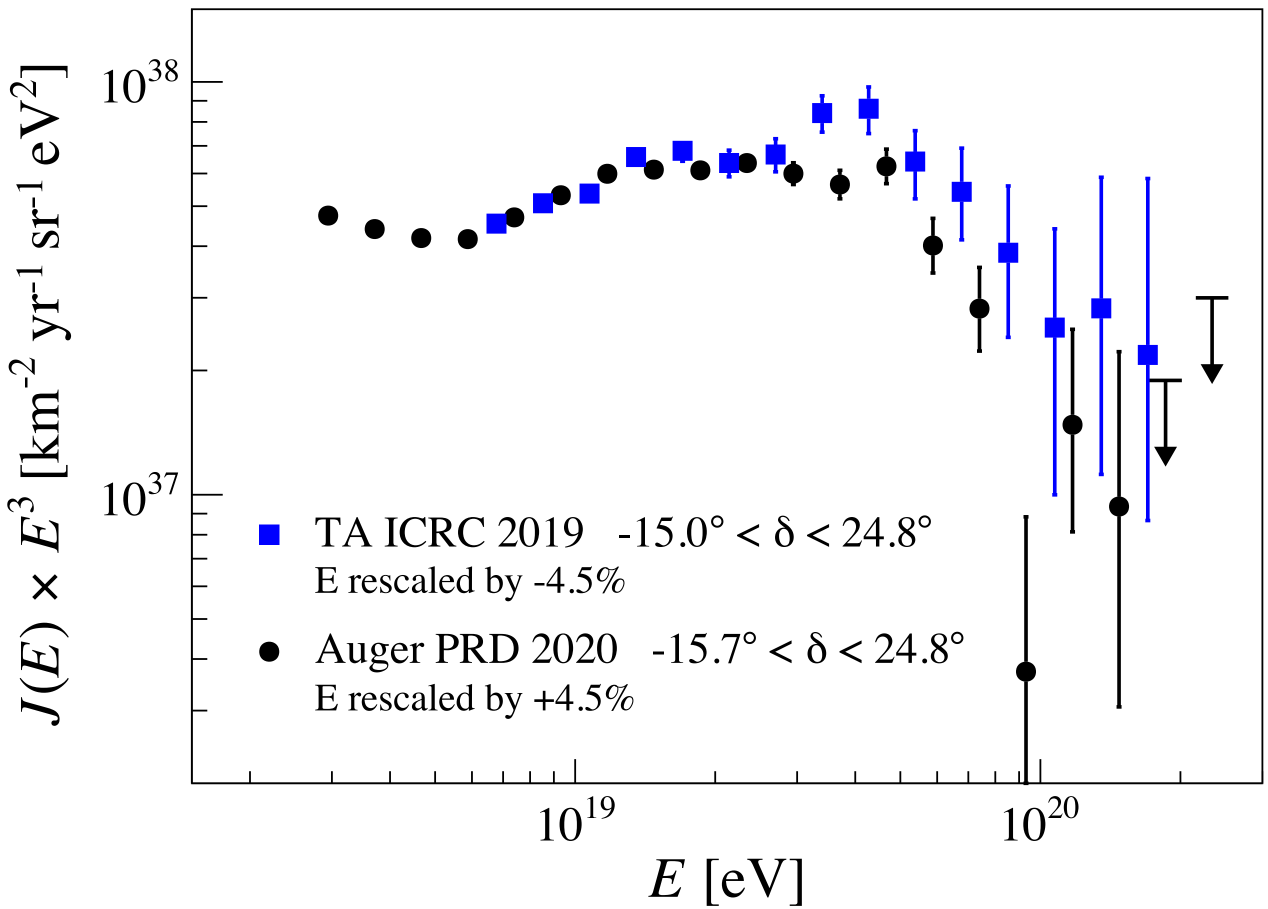
a caveat:



Auger measurements only above full trigger efficiency

ENERGY SCALE: AUGER vs TA

Auger and TA, UHECR 2022, ICRC2023



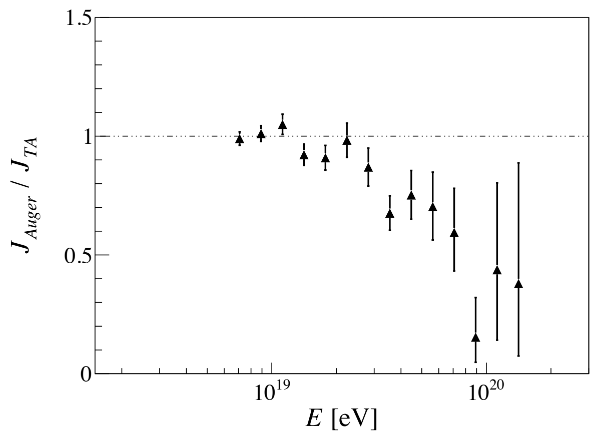
Significant discrepancy persists at the highest energy in the <u>common declination band</u> (no astrophysical effects)

ΔE/E = 20%/decade

statistical significance: 3σ

?

<u>energy dependence of FD systematics small</u>



EXTREMELY ENERGETIC EVENTS (> 10^{20} eV)

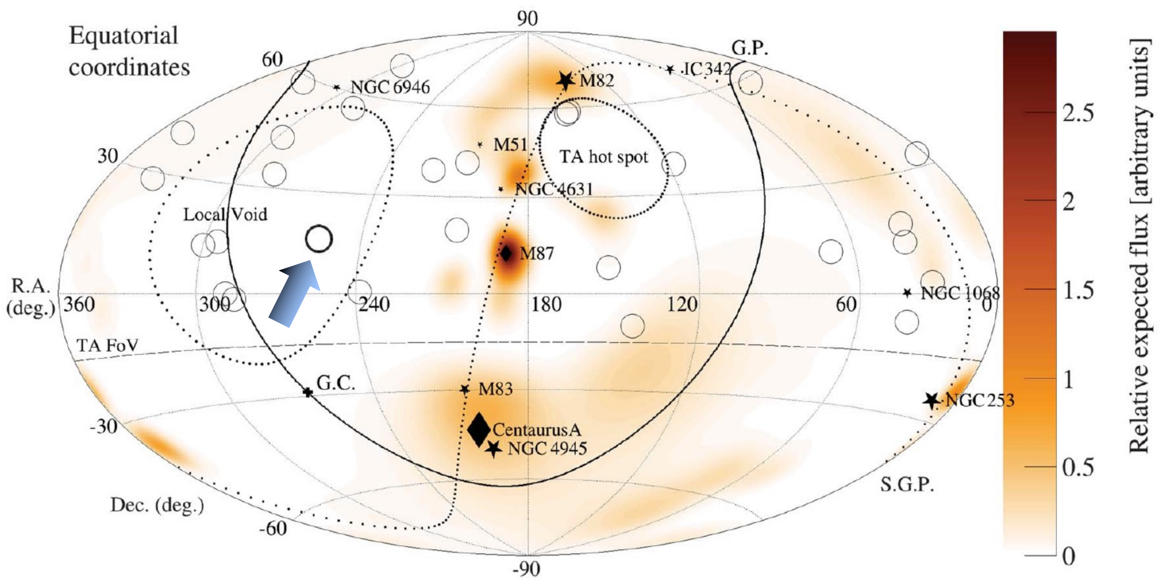
Amaterasu particle
244 EeV

TA, Science 382, 903–907 (2023)

Time (UTC)	Energy (EeV)	S_{800} (m^{-2})	Zenith angle	Azimuth angle	R.A.	Dec.
27 May 2021 10:35:56	244 ± 29 (stat.) $^{+51}_{-76}$ (syst.)	530 ± 57	38.6 ± 0.4°	206.8 ± 0.6°	255.9 ± 0.6°	16.1 ± 0.5°

common band !

From local void. Large magnetic deflections? Physics beyond SM?



Combining Auger and TA data difficult due to the mismatch in the energy scales

see also Auger TA WG on arrival directions, ICRC 2023

166 EeV: most energetic Auger event
note: exposure Auger / TA ≈ 6,7 !

energy of the Amaterasu particle at the Auger energy scale would be 154 EeV

$$-9\% - 20\%(\log_{10}E - 19) = -37\%$$

	E [EeV]	Dec [deg.]
PAO191110	166	-52
PAO070114	165	-21
PAO200611	155	-48
PAO141021	155	-38
TA Amaterasu	154	16

Auger, Astrophys. J. Suppl. S. 264 (2023) 50
https://opendata.auger. org/catalog/

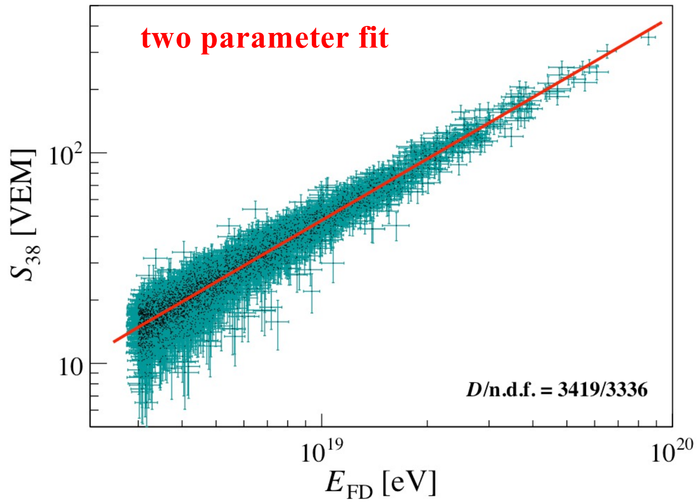
OTHER SYSTEMATICS NOT RELATED TO FD?

Auger

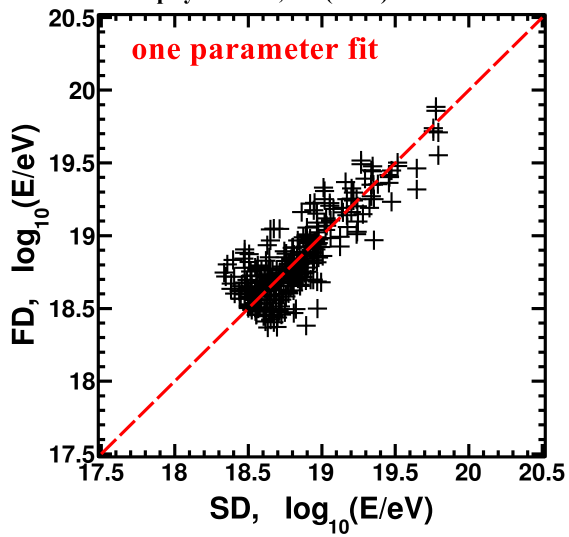
E = A $(S_{38})^B$

data driven SD energy estimator calibrated with a power law

Phys. Rev. D 102, 062005 (2020)



Astrophys. J. 768, L1 (2013)



TA

$$E = \frac{E^{TBL}}{1.27}$$

MC energy calibrated with a non energy dependent rescaling factor

difficult task

- lack of hybrids at the highest energies
- several details on SD and FD rec. maybe important
- e.g.: biases in TA MC energy fully corrected by 1/f ?

TA, Science 382, 903–907 (2023)

Amaterasu particle	E^{TBL} [EeV] from S_{800} = 530 m^{-2}	
Hadr. Int. model	proton	iron
QGSJetII-03	309	-
QGSJetII-04	300	272
EPOS-LHC	261	240

$$E = \frac{E^{TBL}}{f_{model,\ mass}}$$

mass composition is energy dependent !

V. Novotny, this conference

SHOWER ENERGY WITH THE RADIO DETECTOR

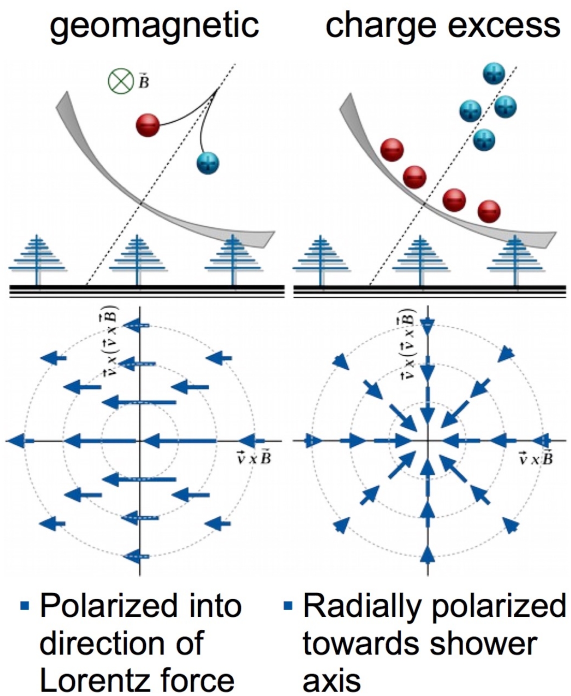
nowadays well understood detection technique

being installed in all Auger SD stations **M. Roth, this conference**

competitive energy estimate compared to FD

T. Heuge Phys. Rep. 620, 1-52 (2016)

	FLUORESCENCE	**RADIO**
yield	**measured in lab**	**QED**
emission	**isotropic**	**forward**
simulation	**no**	**yes**
atmospheric attenuation	yes	no
duty cycle	15%	100% (inclined showers)



Askaryan effect
25% of e^- over e^+

G. Askaryan,
Soviet Phys. JETP 14, 441 (1962)

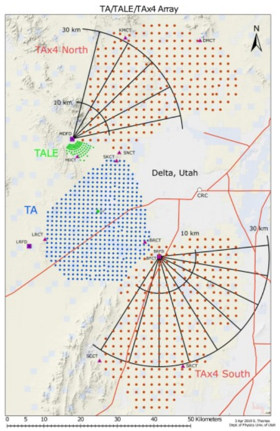
OUTLOOK

- **hybrid detection technique successful**
  - **uncertainty in the (FD) energy scale ≈ 15%**
  - **hard to improve it (absolute calibration of the telescopes)**

- **still systematics on energy estimation not understood at the highest energies**
  - **important to combine the Auger and TA data (full sky coverage)**
  - **difficult problem (lack of hybrids at highest energies, details in reconstruction, …)**

- **future perspectives**
  - **more statistics with AugerPrime and TAx4**
  - **better understanding of the systematics**
    - **scintillators also in Auger**
    - **radio detector**

M. Roth, C. Jui, this conference



END

UNCERTAINTY IN (FD) ENERGY SCALE

AUGER

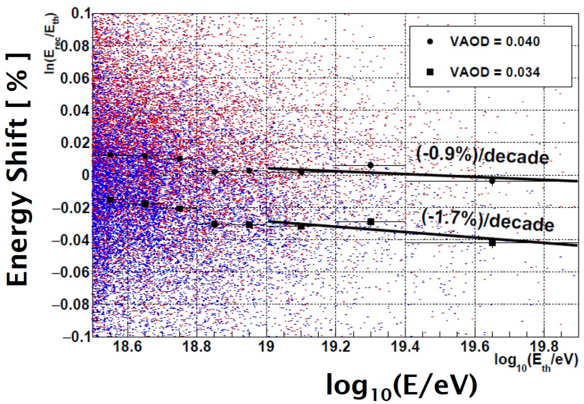
ICRC 2013 arXiv:1307.5059

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

TA

Astropart.Phys. 61 (2015) 93-101

Item	Error (%)	Contributions
Detector sensitivity	10	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11	model (10%), humidity (4%), atmosphere (3%)
Reconstruction	10	model (9%) missing energy (5%)
Sum in quadrature	21	



Aerosols correction larger at larger energies (more far away showers)

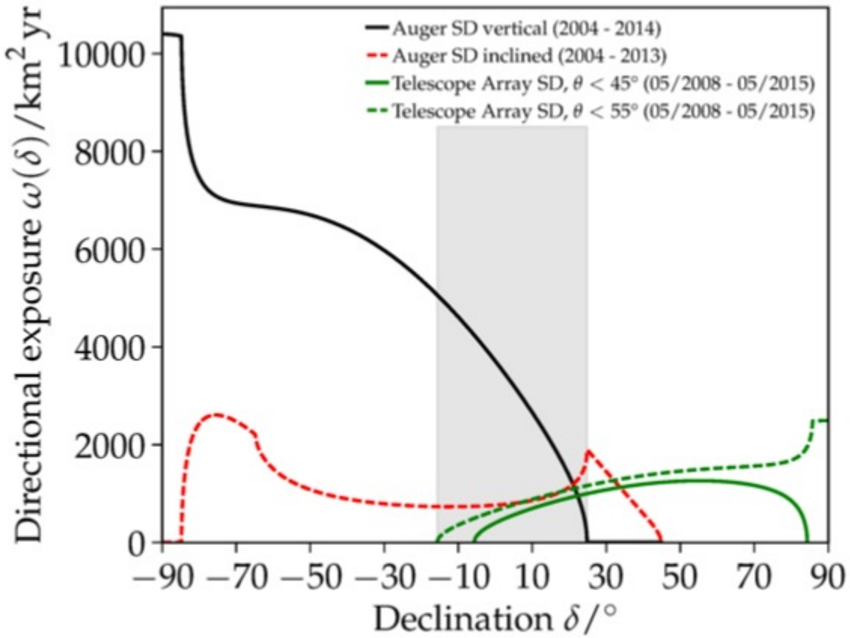
but nonlinearity effects can't explain the 20%/decade energy shift

D. Ivanov, UHECR 2018
V. Harvey, ICRC 2023

TA 21% Auger 14% both almost energy independent

Auger-TA Common Declination Band Spectrum Analysis

Auger and TA, UHECR 2016, ICRC 2017



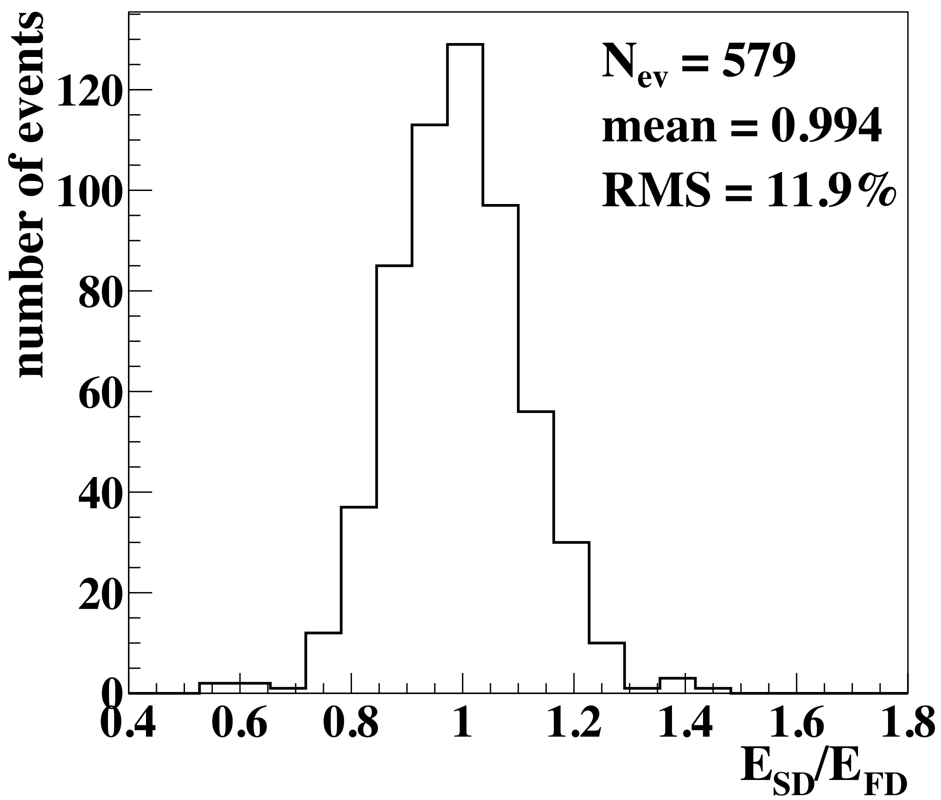
- Restrict δ to [-15° ,24.8°] range
  - Excludes TA hot spot
- Inependence of exposure on declination (aka "1/ω method"):

$$J_{1/\omega}(E) = \frac{1}{\Delta\Omega\Delta E}\sum_{i=1}^{N}\frac{1}{\omega(\delta_i)}$$

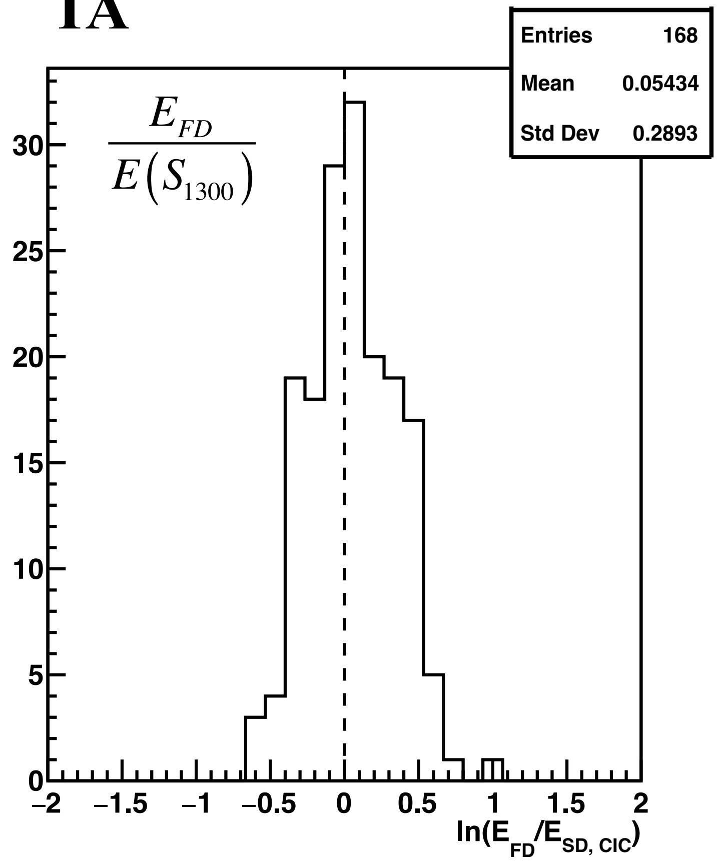
(UHECR 2016 proceedings)

Discrepancy persists also considering the different shape of the the directional exposure

AUGER



TA



Auger and TA, UHECR 2022

Auger and TA, UHECR 2022