The energy spectrum of ultra-high energy cosmic rays measured at the Pierre Auger Observatory and the Telescope Array

PIERRE AUGER OBSERVATORY

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on behalf of the Pierre Auger and Telescope Array collaborations

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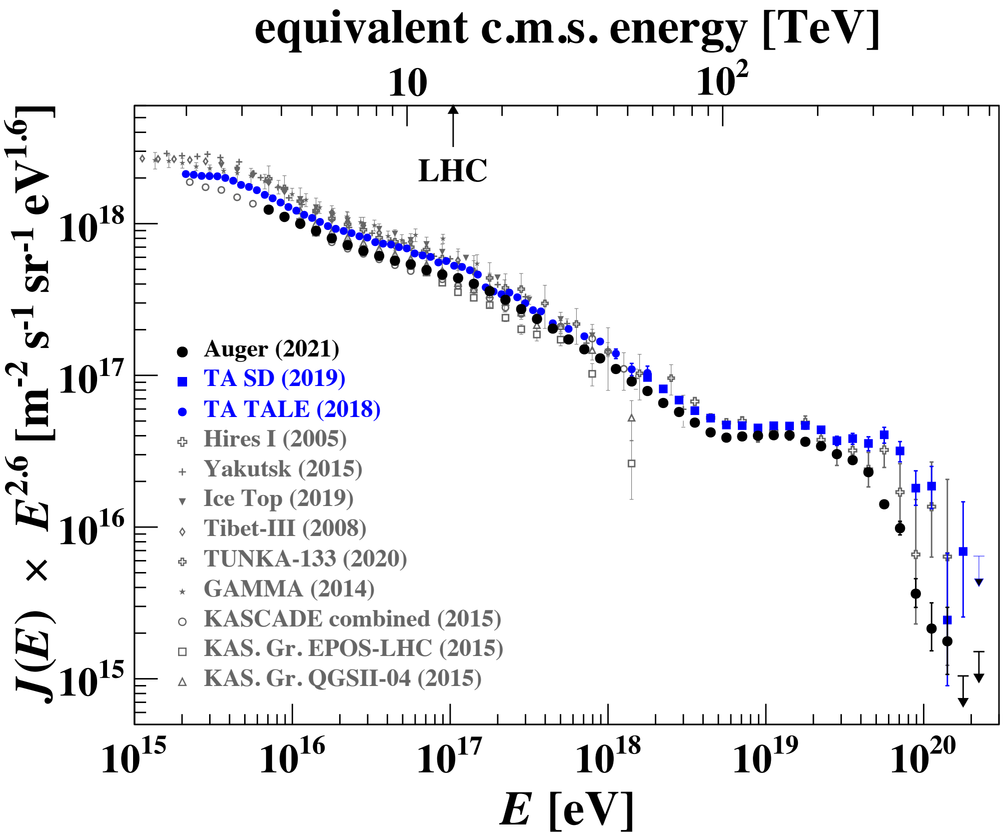
TELESCOPE ARRAY PROJECT

6th International Symposium on Ultra High Energy Cosmic Rays
UHECR 2022
L'Aquila, Italy October 3 - 7 2022

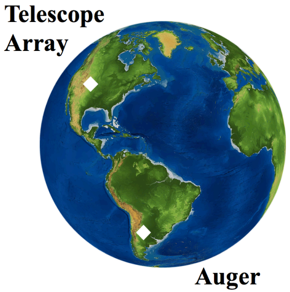
The joint Auger TA working group on energy spectrum



Understand the difference among the measurements at the UHEs:

- **information on astrophysical phenomena**
- **correct combination of the data to achieve the full sky coverage**

see F. Urban at this conference



UHECR 2010	Nagoya, Japan
UHECR 2012	Cern, Geneva
UHECR 2014	Springdale (Utah), USA
UHECR 2016	Kyoto, Japan
ICRC 2017	Busan, Korea
UHECR 2018	Paris, France
ICRC 2019	Madison, USA
ICRC 2021	Berlin, Germany

UHECR Hybrid Observatories

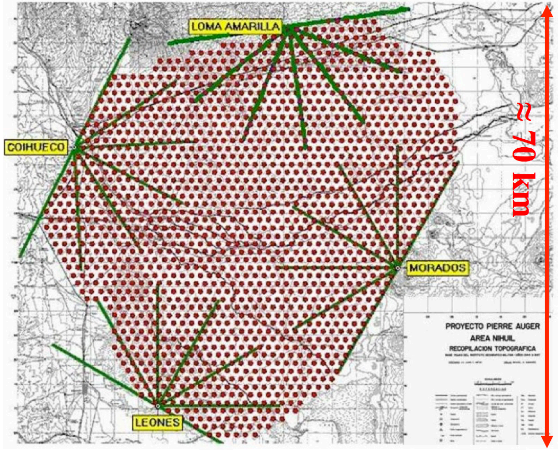
PIERRE AUGER OBSERVATORY

Malargüe Mendoza
(Argentina)
35^0 S latitude

3000 km^2

1660 WCDs
1500 m spacing
triangular grid

4 FD sites



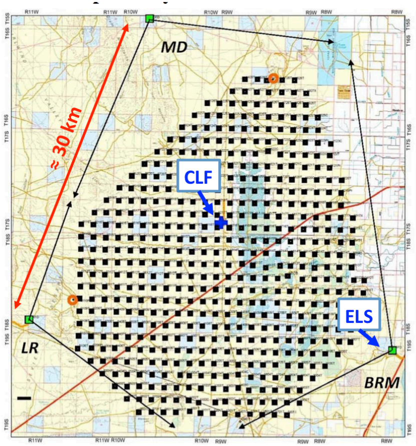
TELESCOPE ARRAY

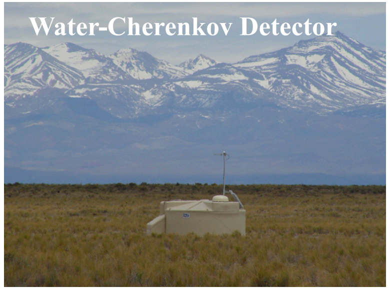
Millard County
Utah (USA)
39^0 N latitude

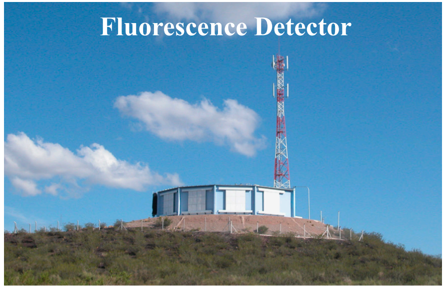
700 km^2

507 scintillators
1200 m spacing
square grid

3 FD sites




Water-Cherenkov Detector

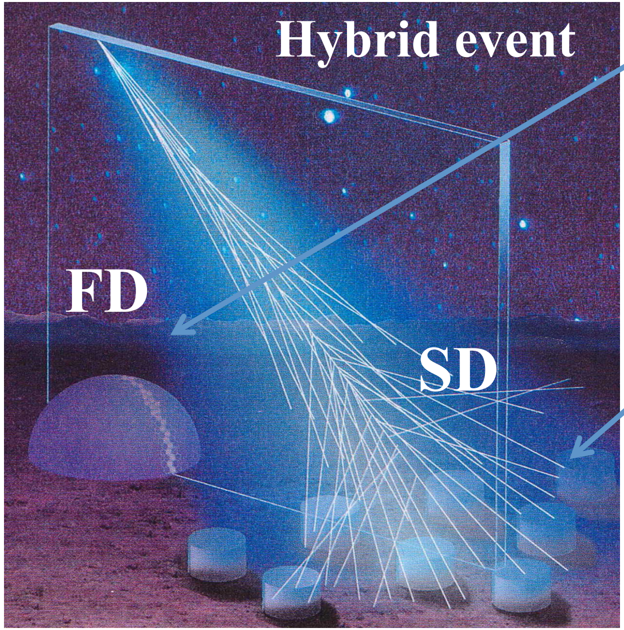

Fluorescence Detector


Scintillator

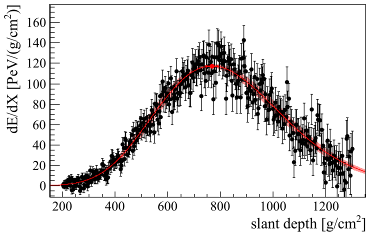

Fluorescence Detector

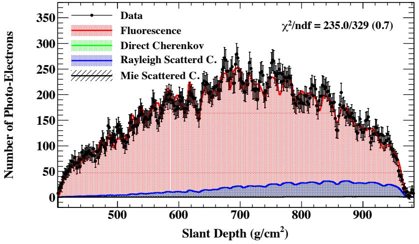
The hybrid detection technique

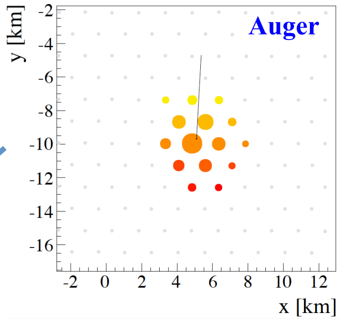
15% duty cycle

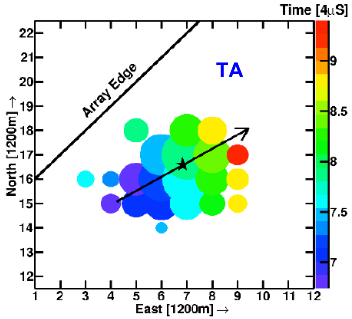


100% duty cycle









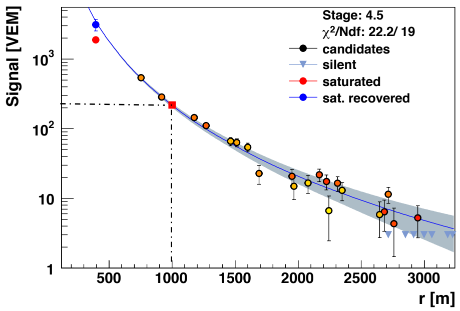
UHECR spectrum

- **high efficiency of SD**
- **calorimetric energy scale from FD**

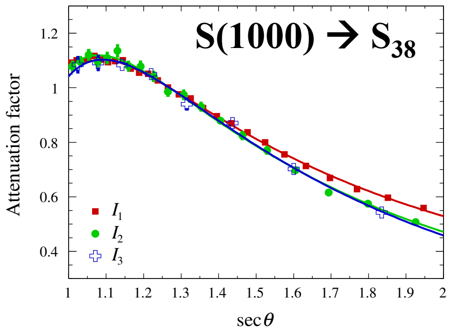
The experimental techniques

Auger

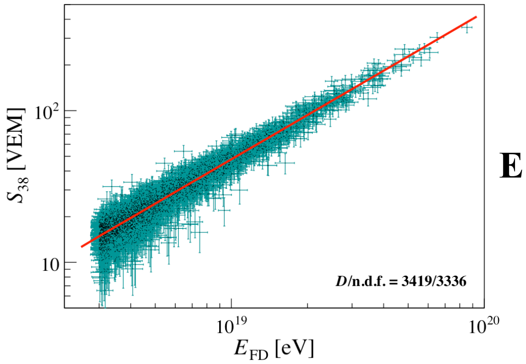
S(1000)



attenuation from CIC



power law from hybrids

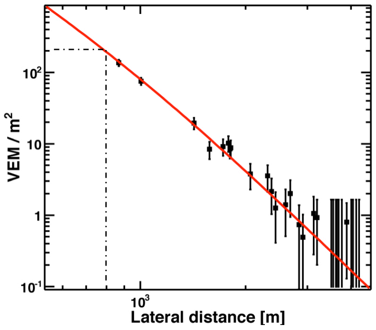


$$E = A\,(S_{38})^B$$

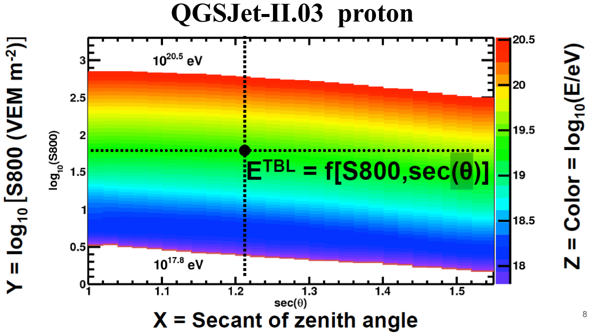
$B \approx 1$

TA

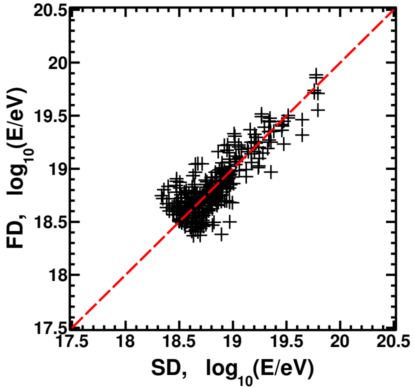
S(800)



energy from MC look-up table



rescaling factor from hybrids



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

full trigger efficiency $> 10^{18.8}$ eV

The energy scale

AUGER

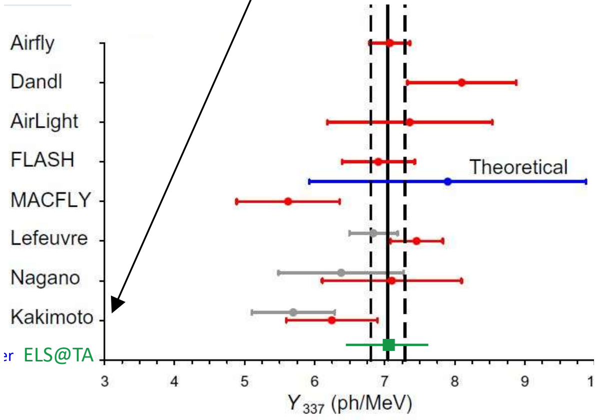
Proc. 34 ICRC 2013 (Rio de Janeiro, Brazil)
[arXiv:1307.5059]

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

Proc. 32nd ICRC 2011 (Beijing, China), 12, 67 (2011)
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	



Auger uses Airfly
Astrop. Phys. 42. 90 (2013)
Astrop. Phys. 28, 41 (2007)

figure from M. Fukushima, GCOS workshop 2022

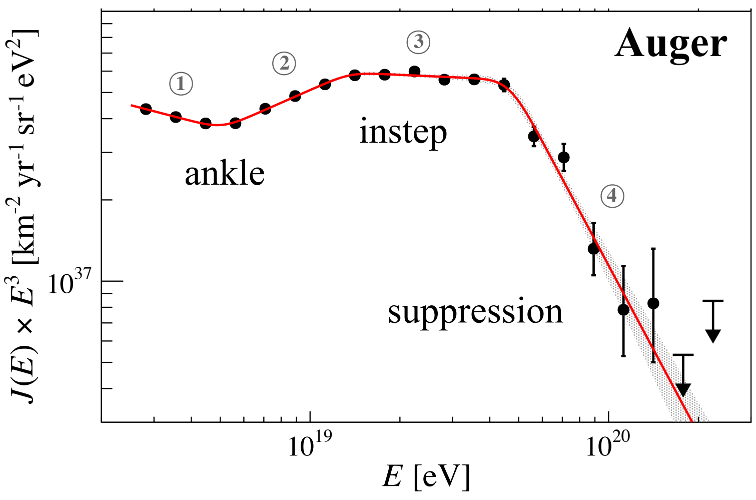
TA uses Kakimoto et al.
NIM-A 372, 527 (1996)
+FLASH spectrum

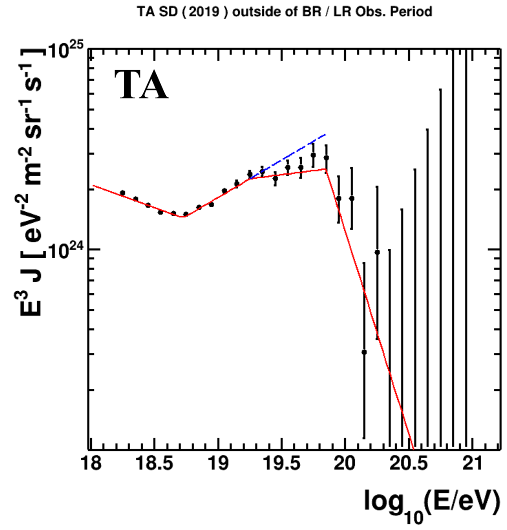
TA 21% Auger 14% both almost energy independent

Measurements at the two observatories

see next talks by S.Ogio and Q.Luce

Auger, Phys. Rev. D 102 (2020) 062005
TA, PoS (ICRC2019) 298
see also WG report PoS (ICRC2021) 337

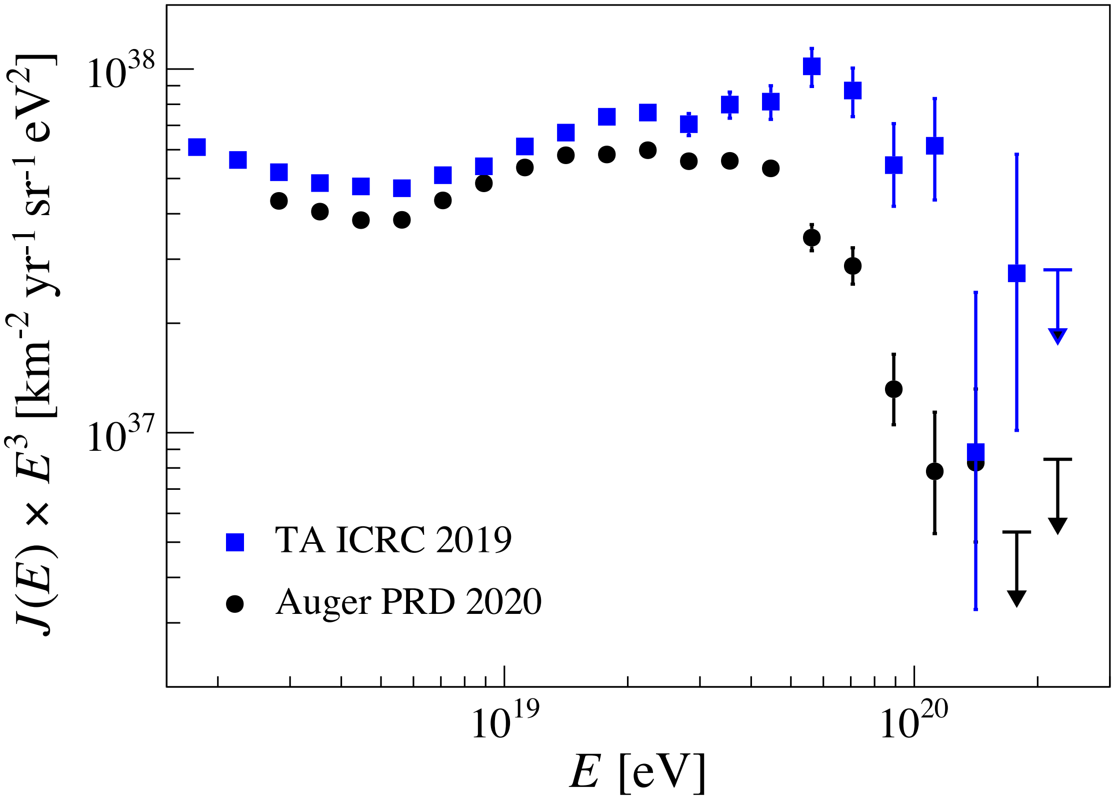




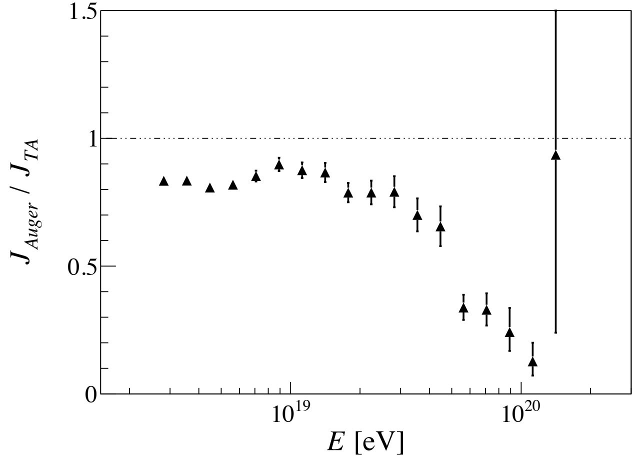
Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
E_{ankle}/EeV	5.0 ± 0.1	5.4 ± 0.1
E_{instep}/EeV	13 ± 1	18 ± 1
E_{cut}/EeV	46 ± 3	71 ± 3

- **same characterization of the spectral features**
- **agreement at the ankle and some tension at highest energies**
- **common declination band to disentangle astrophysical from experimental effects: $-15^o < \delta < 24.8^o$**

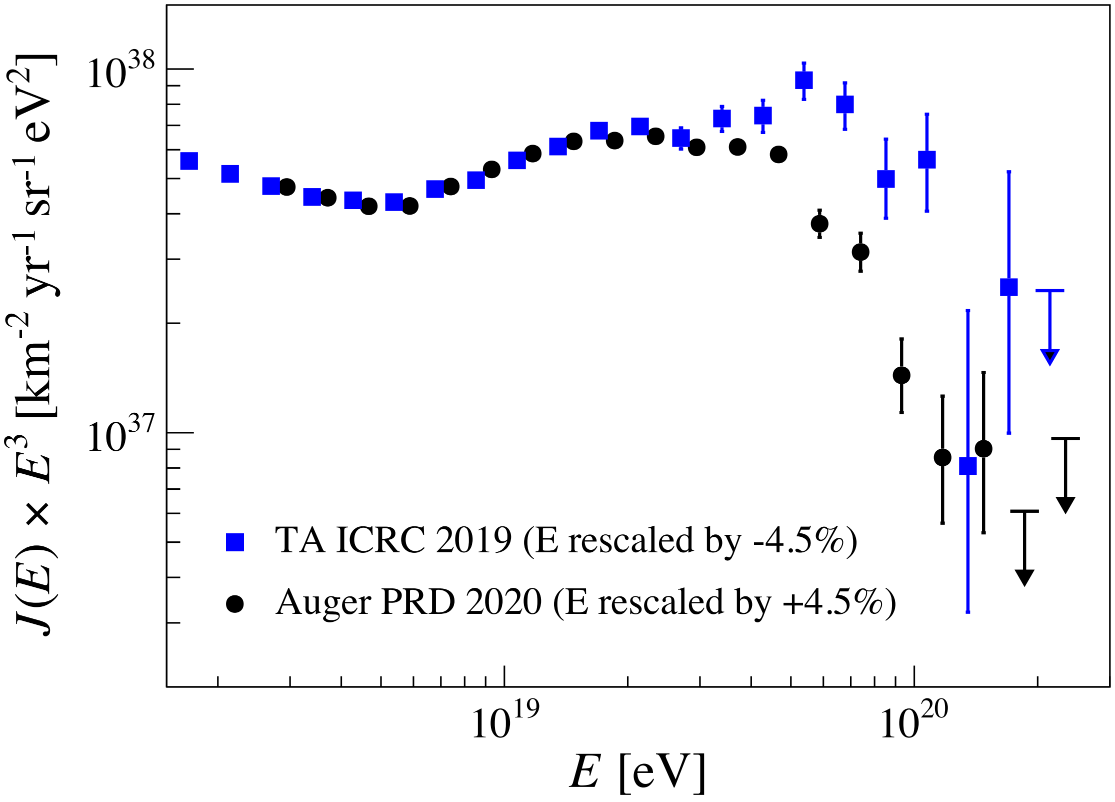
Measurements in the full sky



ratio of Auger to TA energy spectrum

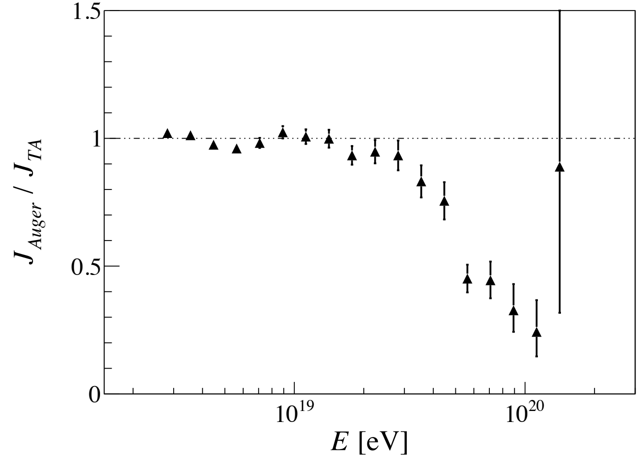


Measurements in the full sky



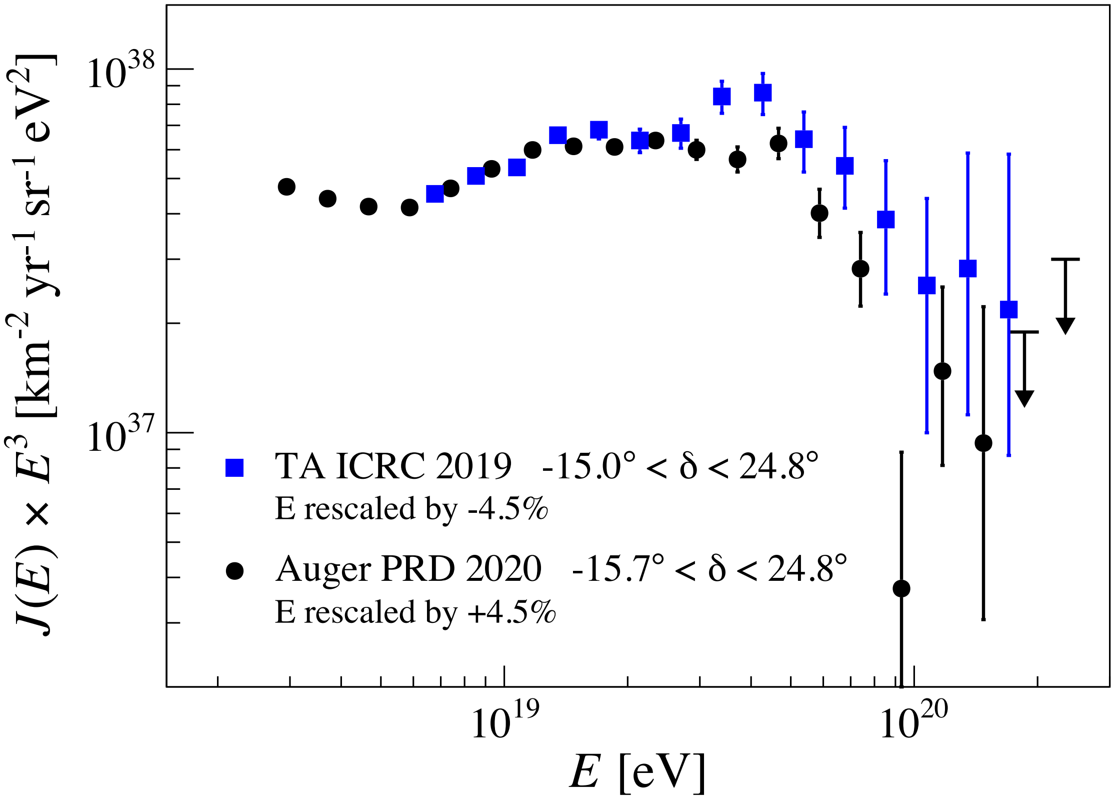
good agreement up to ≈ 10^{19} eV after an overall 9% rescaling of the energies

significant discrepancy at the highest energies

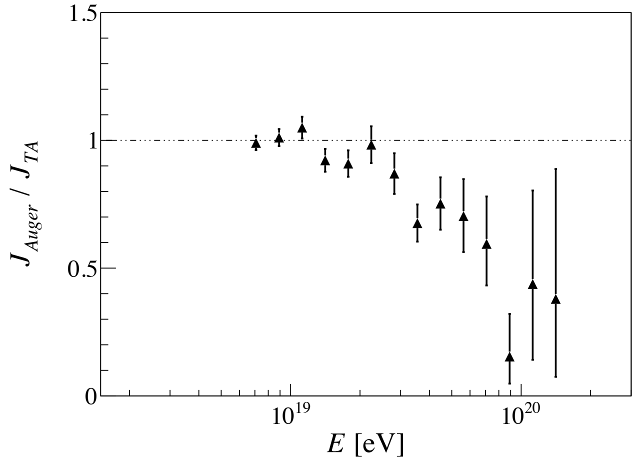


Measurements in the common declination band

note: TA full trigger efficiency $E>10^{18.8}$ eV



discrepancy at the highest energies persists in the common declination band



Measurements in the common declination band

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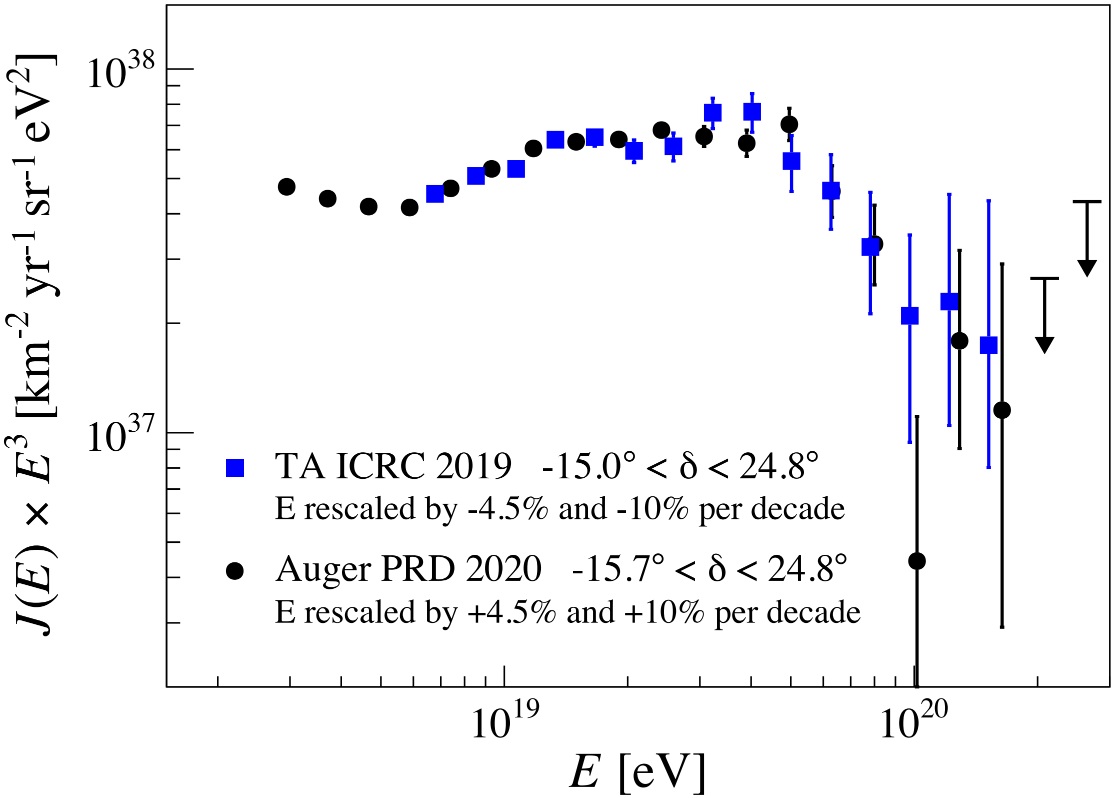
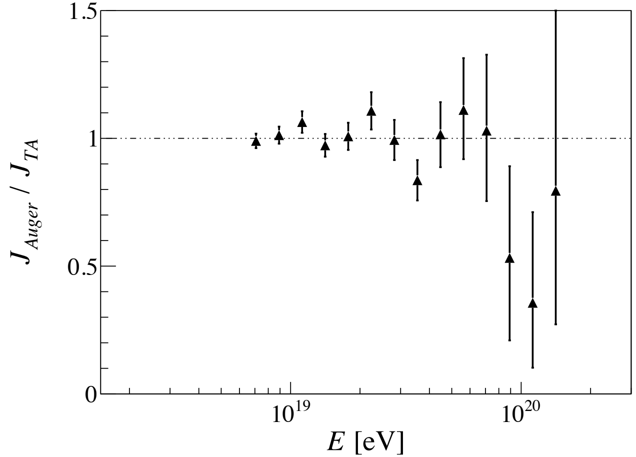


discrepancy at the highest energies removed introducing an energy dependent energy shift

overall 20%/decade for E>10^{19} eV



Measurements in the common declination band

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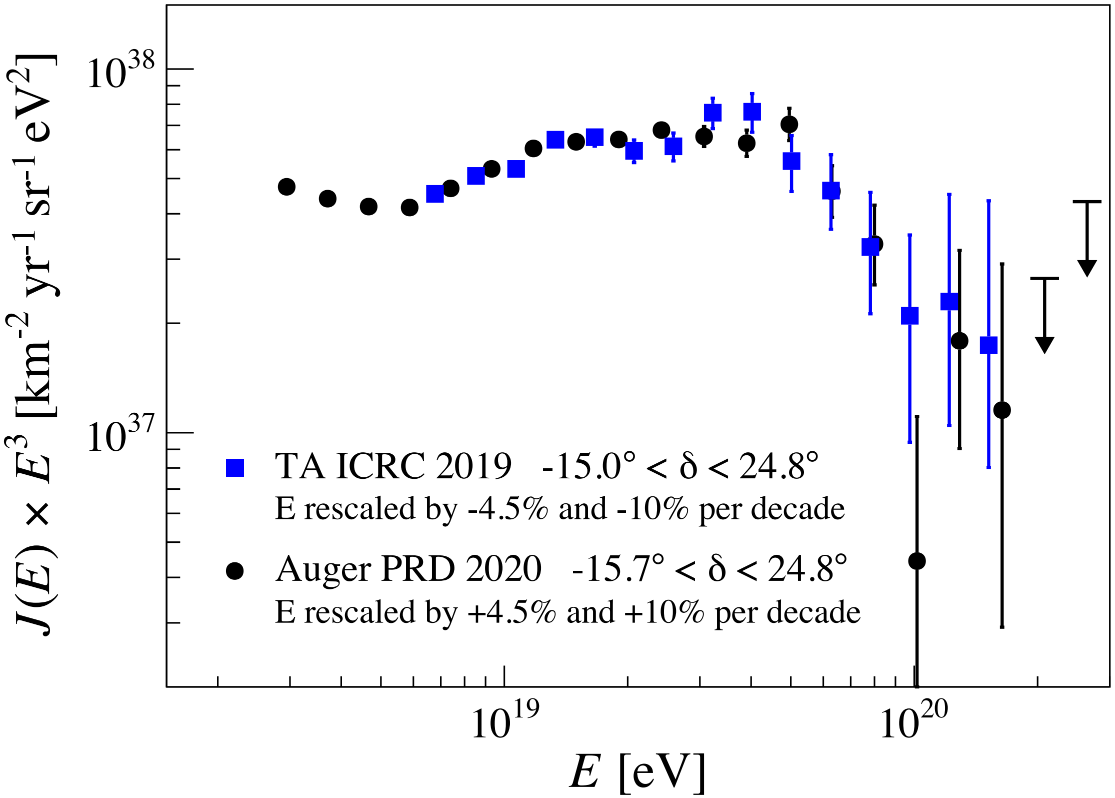

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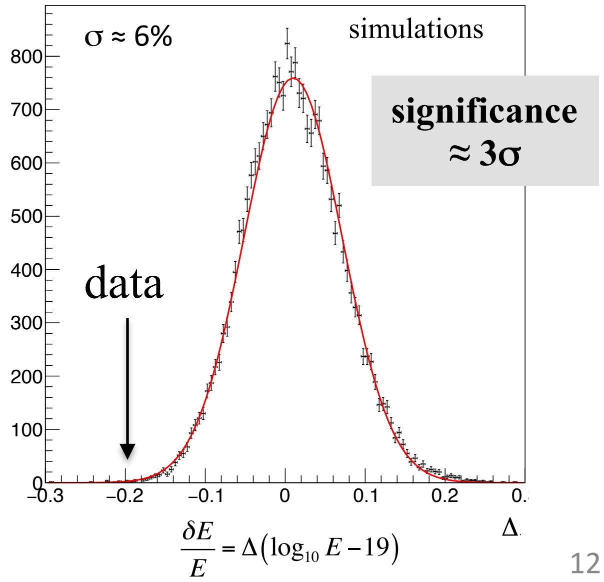
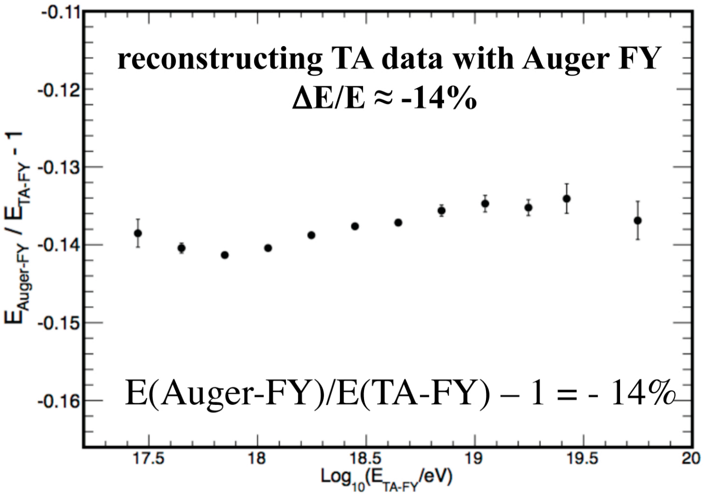


- the overall 9% energy shift in agreement with the uncertainties in the energy scale
- (from UHECR 2014 report) 9% would be further reduced to < 5% if the FD events would be reconstructed using the same "external" parameters

≈ 9%-14%+7%

Fluorescence yield

Auger: AirFly TA: Kakimoto et al. + FLASH spectrum

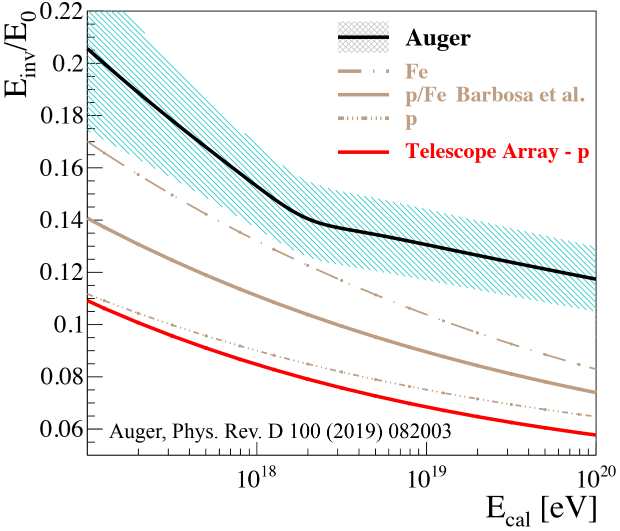


TA energies reduced by -14% using the Auger fluorescence yield

Invisible energy

Auger from SD sensitivity to μ

TA from p simulations



$E_{inv} \propto N_{\mu}$

N_{μ} excess

TA energies increased by +7% using the Auger invisible energy

Biases in the shower size reconstruction that can't be corrected by the energy calibration ?

TA - scintillator
square grid
1200 m
AGASA LDF

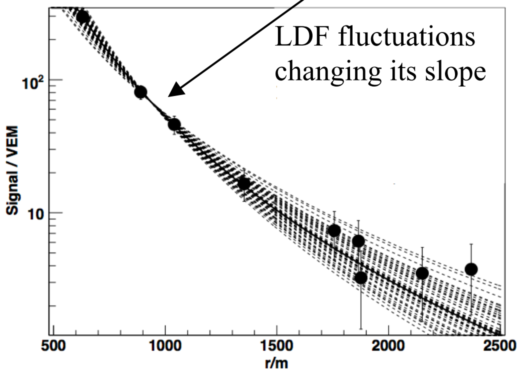
$$S(r) = A\left(\frac{r}{91.6\ \mathrm{m}}\right)^{-1.2}\left(1+\frac{r}{91.6\ \mathrm{m}}\right)^{-[\eta(\theta)-1.2]}\left(1+\left[\frac{r}{1000\ \mathrm{m}}\right]^2\right)^{-0.6}$$

S(800) from the crossover of the LDF of p and Fe

Auger - WCD
triangular grid
1500 m
modified NKG LDF

$$S(r) = S(r_{opt})\left(\frac{r}{r_{opt}}\right)^{\beta[S(r_{opt}),\theta]}\left(\frac{r+700\ \mathrm{m}}{r_{opt}+700\ \mathrm{m}}\right)^{\beta[S(r_{opt}),\theta]+\gamma[S(r_{opt}),\theta]}$$

β and γ from data
$S(r_{opt}=1000\ \mathrm{m})$

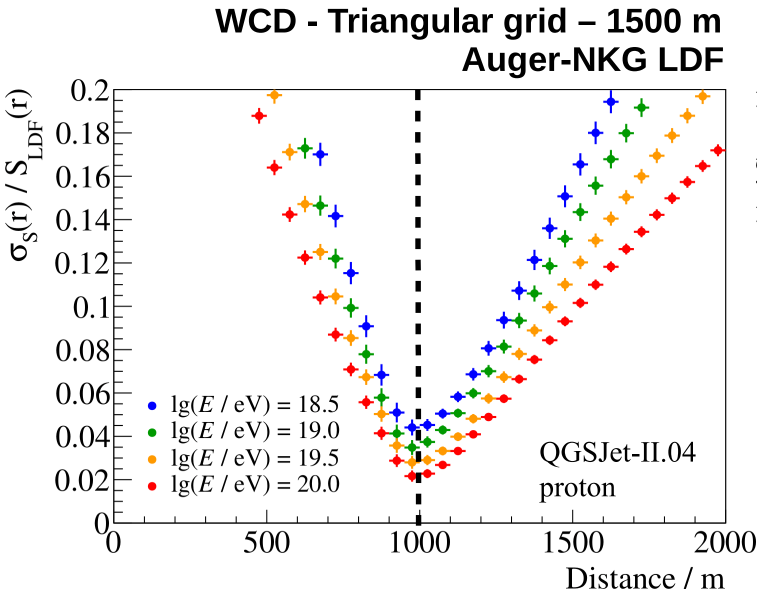


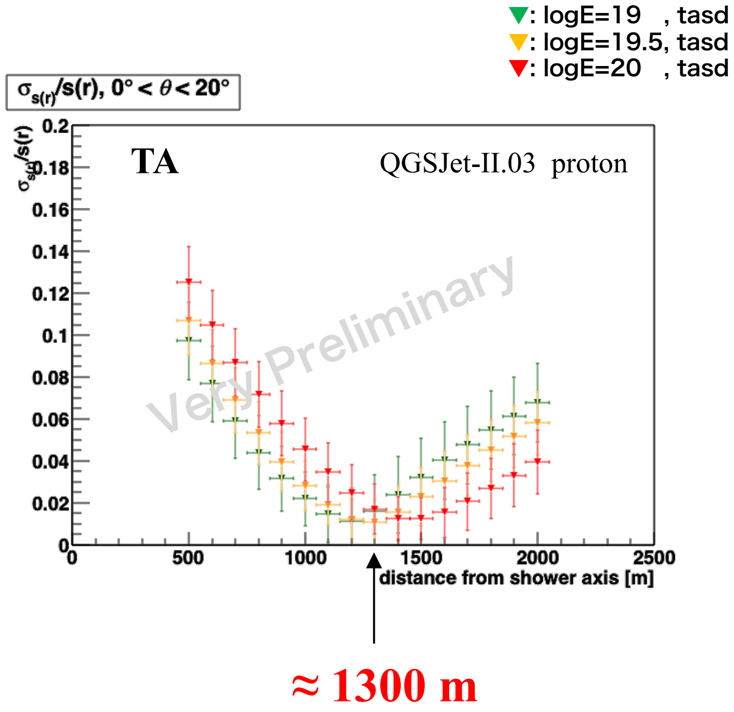
D. Newton et al. Astropart. Phys. 26 (2007), 414

energy estimator at an *optimal* distance (r_{opt}) that minimizes the fluctuations of the LDF

Recent studies by Auger confirm that r_{opt} = 1000 m

For TA the fluctuations are minimized at core distances larger than 800 m



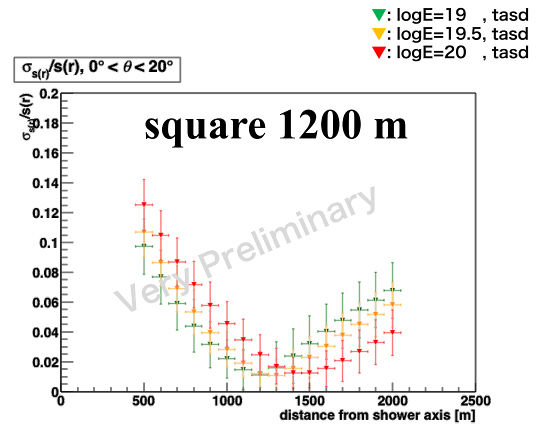


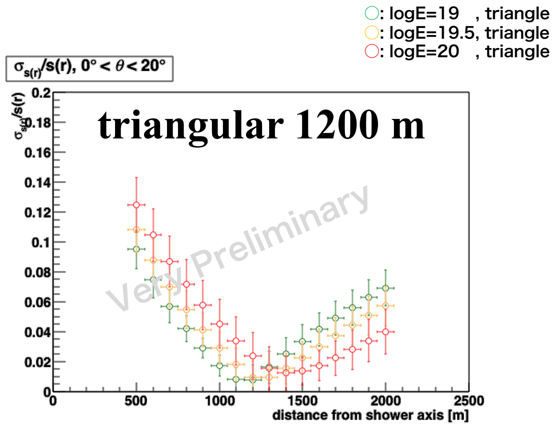
note: for the spectrum, bias effects are much more important than the resolution ones

a complex problem … (spacing, square vs triangular, LDF, detector, ...)

TA simulated events

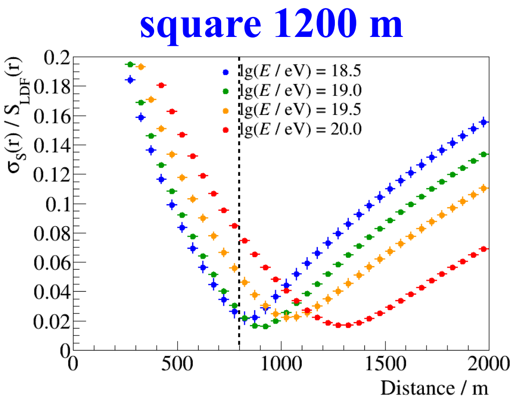
AGASA LDF

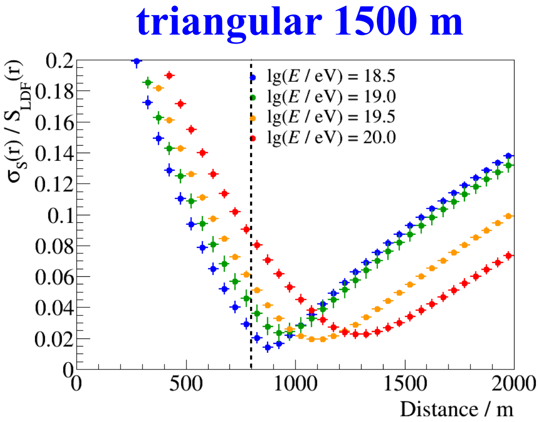




Auger SSD (scintillator) simulated events

AGASA LDF



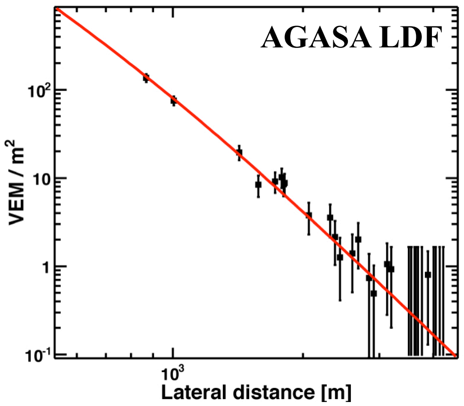


important also for AugerPrime and TA×4 ...

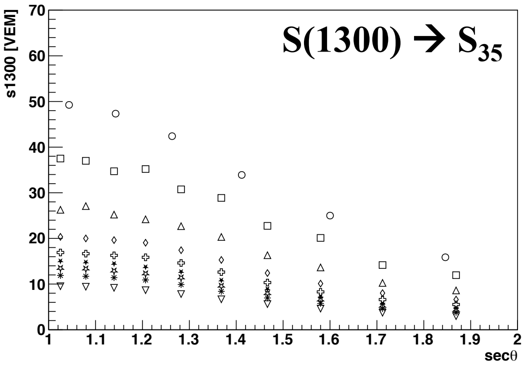
TA: potential biases from not using $S(r_{opt})$?

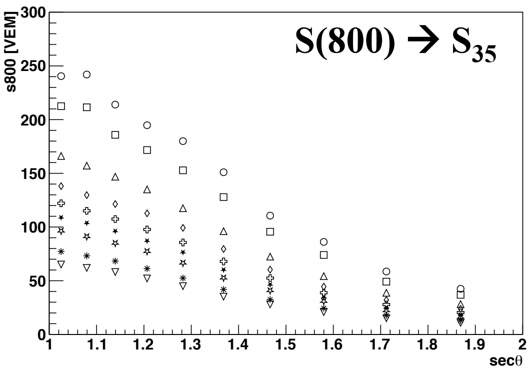
Cross check applying the Auger data-driven analysis to TA data

two energy estimators S(1300) and S(800)

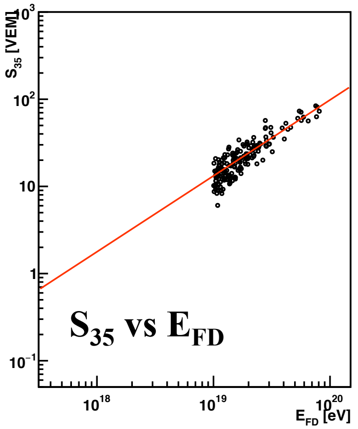


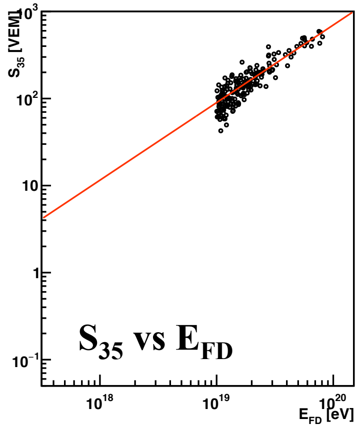
CIC





energy calibration





full trigger efficiency $>10^{19}$ eV

$$E = A\,(S_{35})^B$$

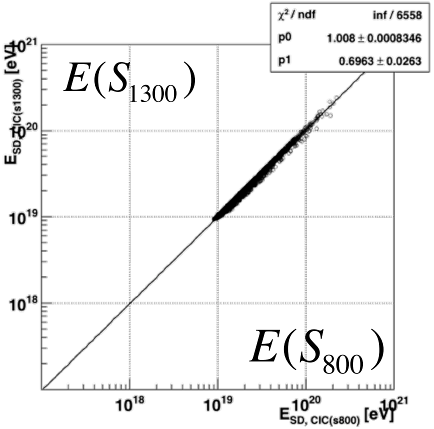
$B \approx 1.05$

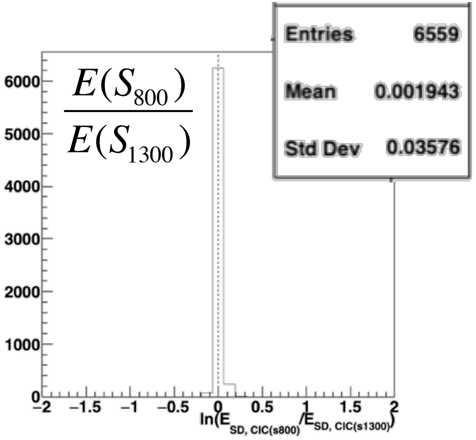
PRELIMINARY

TA: potential biases from not using $S(r_{opt})$?

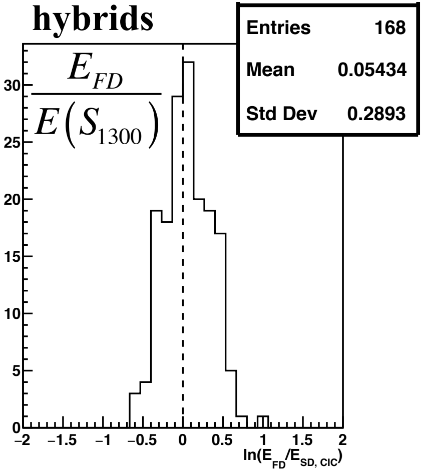
<u>very good agreement between energies from S(1300) and S(800)</u>

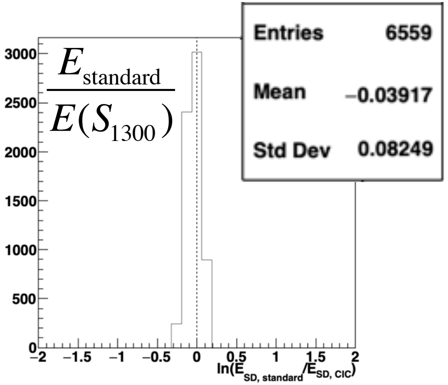
consistency with standard (MC look-up table) energy calculation

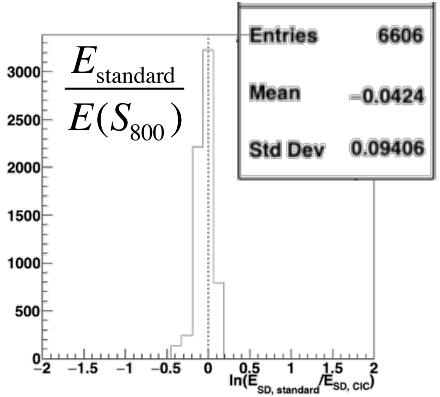




hybrids

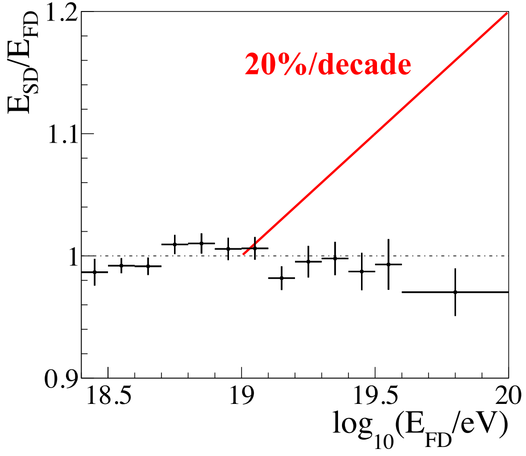


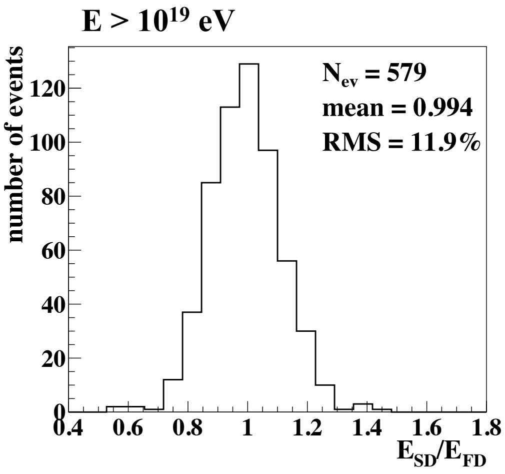




Auger: systematics from the estimation of the shower size ?

- **hybrids events: SD energies well aligned to the FD ones**
- **systematics on flux arising from the uncertainty in S(1000) estimated to be < ±3%**





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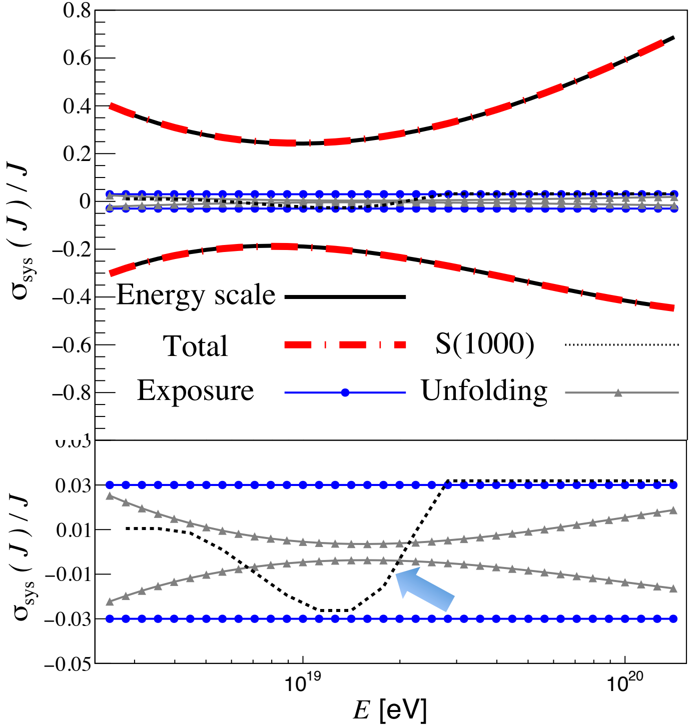
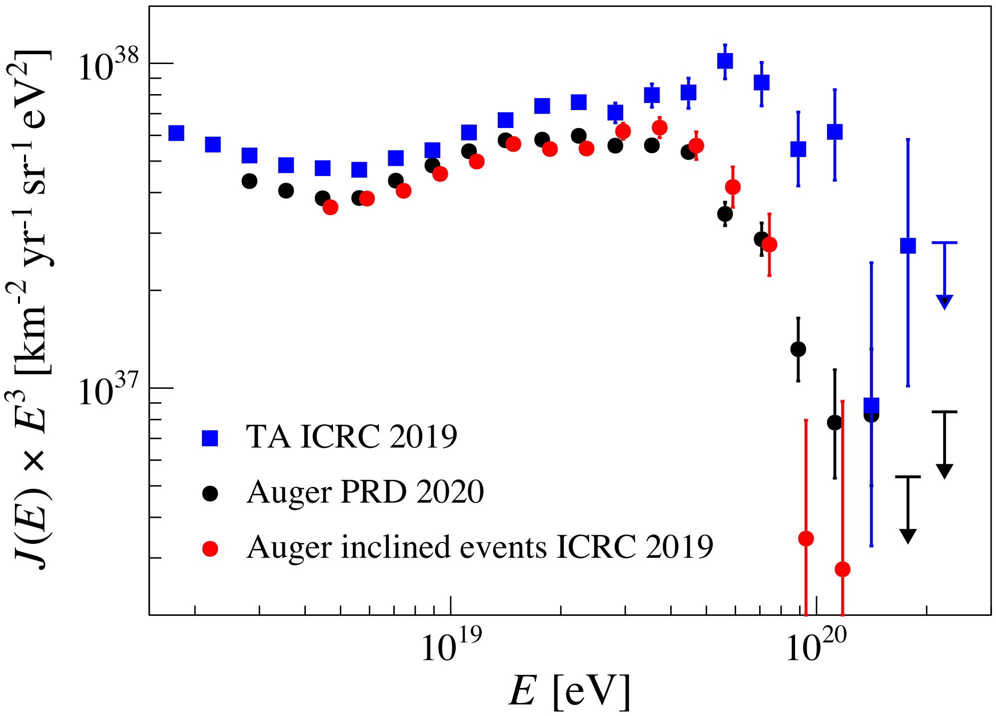
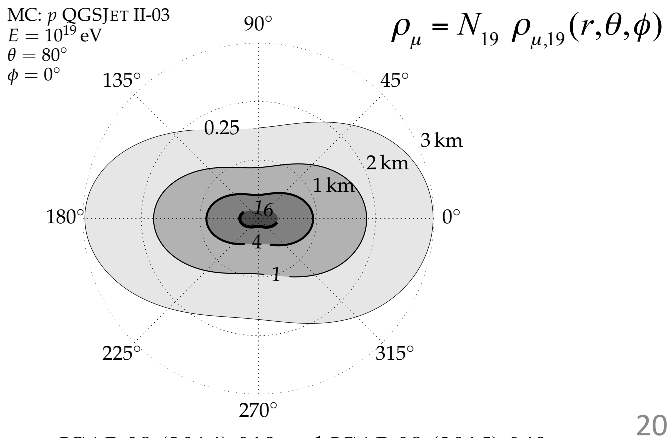


Auger: systematics from the estimation of the shower size ?



Same kind of disagreement using the inclined events (θ > 60⁰)

- **exposure ≈ 30% of the one for θ < 60⁰**
- **require completely different reconstruction technique**
- **calibration of N_{19} using a power law**



Auger, JCAP 08 (2014) 019 and JCAP 08 (2015) 049

Outlook

Further studies of the systematic uncertainties associated to SD reconstruction but the disagreement between the Auger and TA spectrum at the highest energies is not yet understood
(a difficult experimental problem)

More information in the *2nd phase* of the observatories:

- **AugerPrime scintillators**
- **enhanced statistics with TAx4**

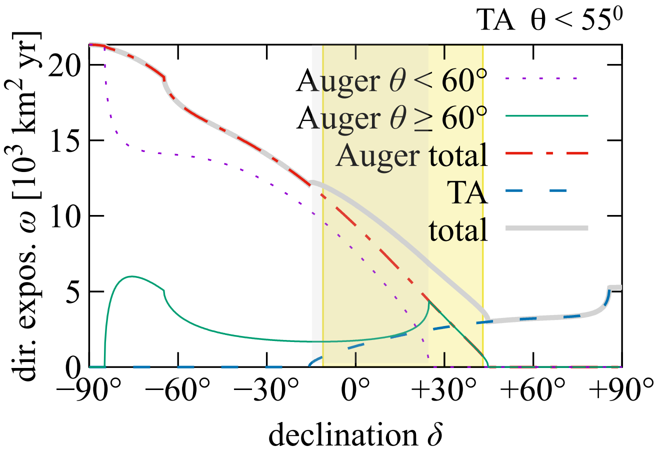
Recommandation from the spectrum WG
given that we are entering in a *2nd phase,* would not be the right time to converge on the use of the same fluorescence yield, and invisible energy ?

(note: energy scales <10^{19} eV would be in agreement at the few % level)

data set

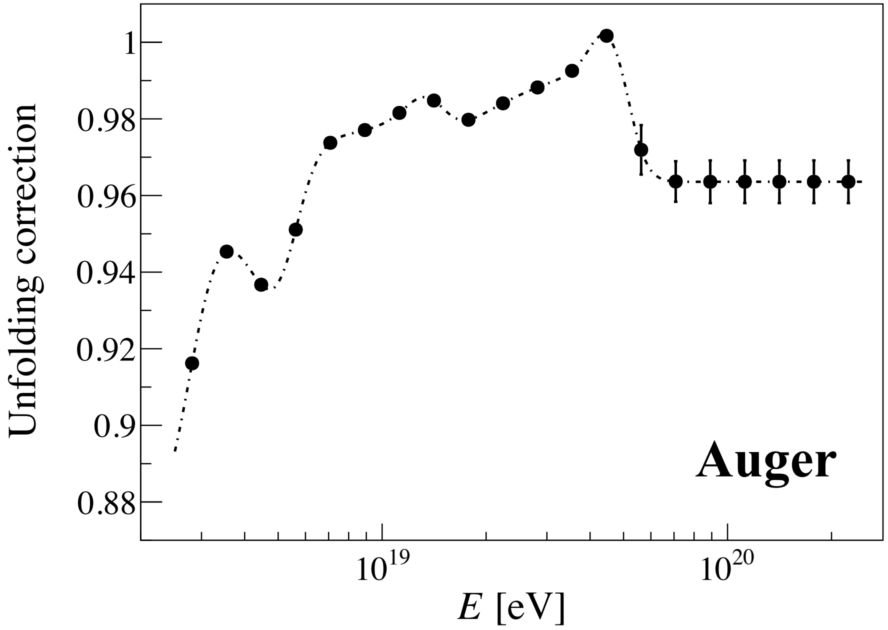
	TA	Auger
data period	11/05/2008 – 11/05/2019	01/01/2004 – 31/08/2018
energy threshold	$10^{18.2}$ eV	$10^{18.4}$ eV
zenith angle	$\theta < 45^0$	$\theta < 60^0$
exposure	≈ 10000 km² sr yr > $10^{18.8}$ eV (full trigger eff.) + res	60400 km² sr yr
$N_{ev} > 10^{19}$ eV (10^{20} eV)	3292 (14)	16737 (15)
SD energy resolution 10^{19} eV - 10^{20} eV	21% - 15%	11% - 8%
FD energy resolution	19%	7.4%
Uncert. energy scale	21%	14%

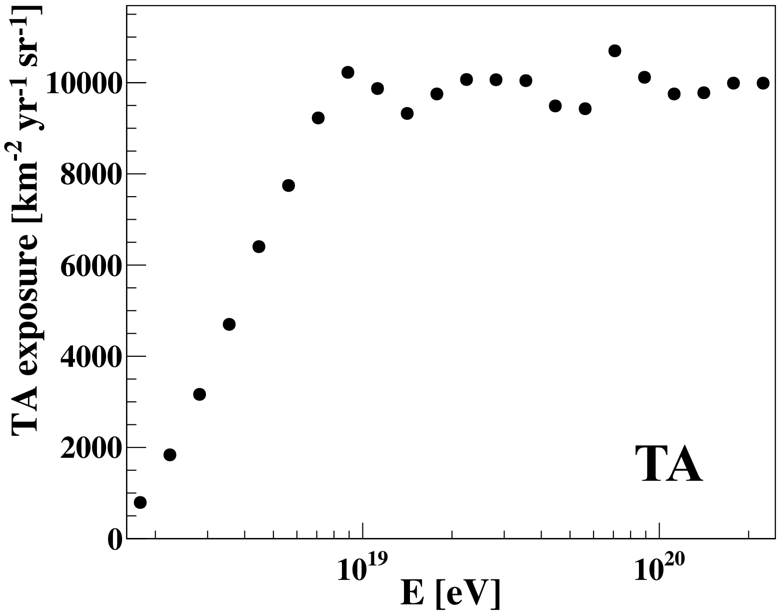
Common declination band: $-15^0 < \delta < 24.8^0$



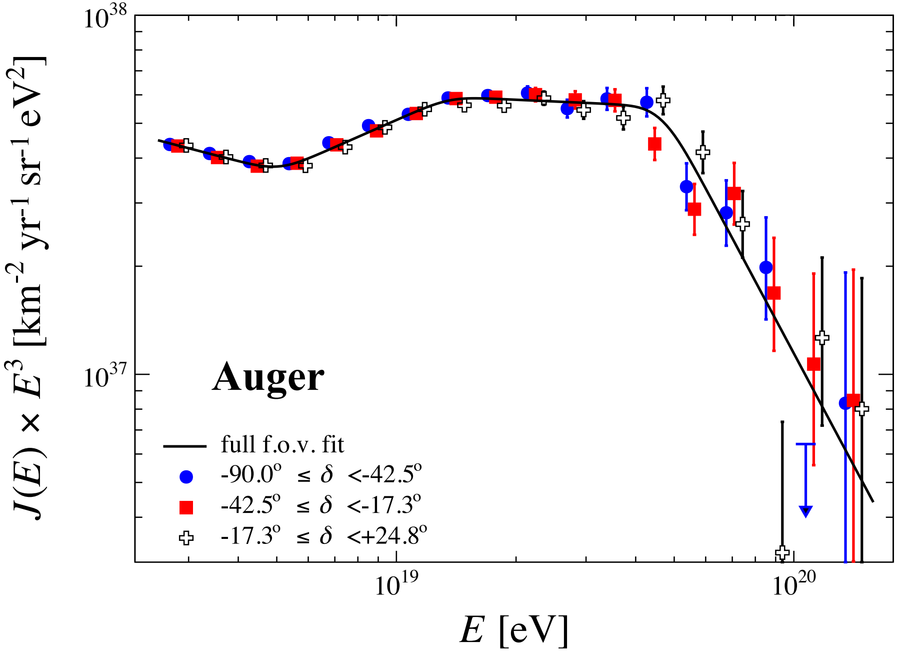
Auger, Phys. Rev. D 102 (2020) 062005
TA, PoS (ICRC2019) 298

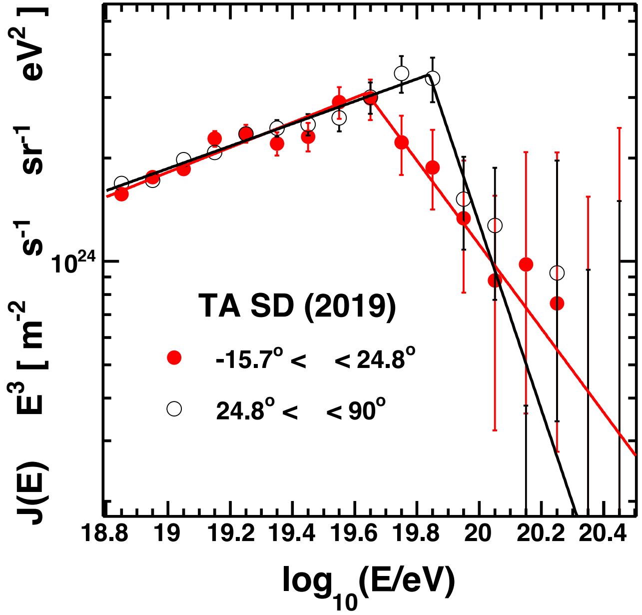
correction for resolution effects to obtain the unfolded spectrum





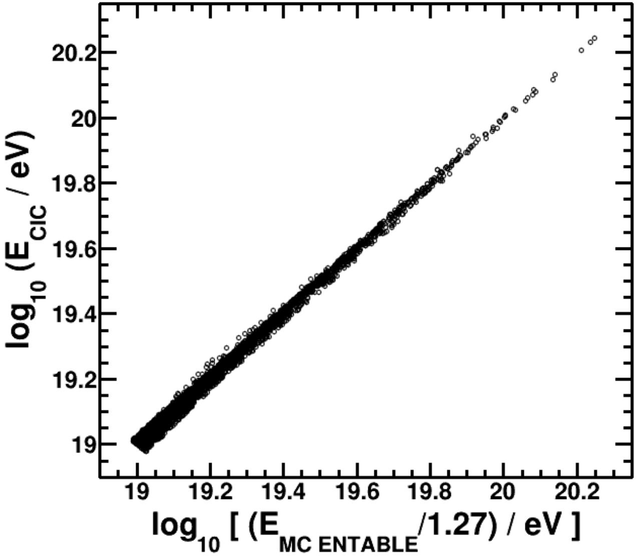
Measurements in different declination bands

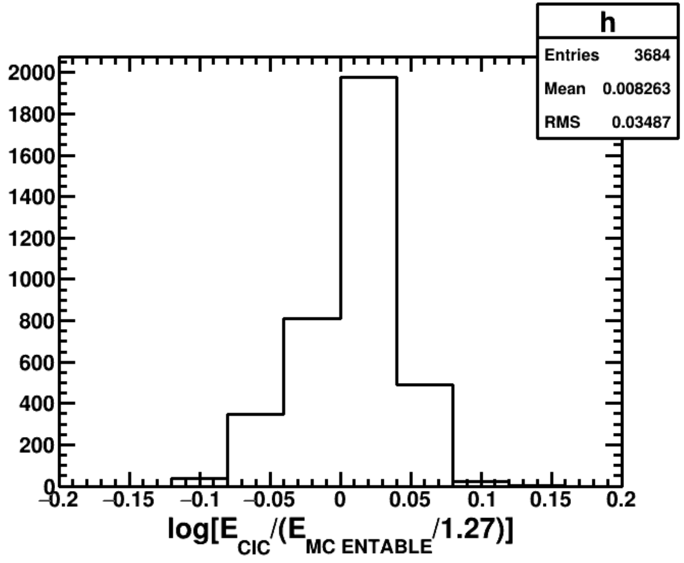




Compare TA Constant Intensity Cut and TA Original Monte Carlo Based Energy Reconstruction Methods

UHECR 2018





TA MC-based and Constant Intensity Cut energy reconstruction methods agree at ~3% level