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Use of the Signal at an Optimal Distance from the Shower Core as Surrogate for Shower Size

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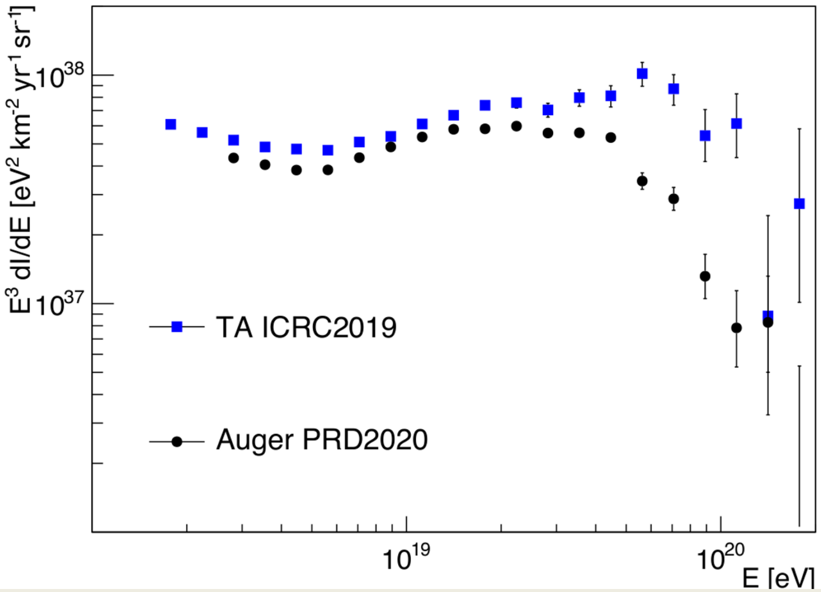
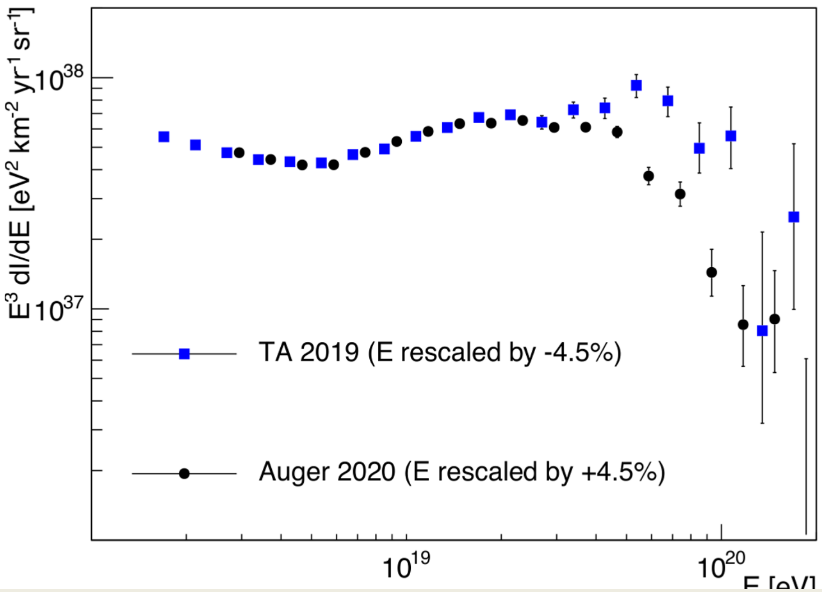
Motivation

An attempt to understand the differences between the energy spectra reported by Auger and TA Observatories

Note: the differences are also seen in the common declination band visible to both instruments





Events on a square grid of Telescope Array reconstructed using the LDF from AGASA (1990s)

Mis-estimation of the estimator of the shower size → impact on the spectrum?

Y. Tsunesada et al. (2021), *ICRC 21*

What to measure to get a good estimate of the energy? Some history

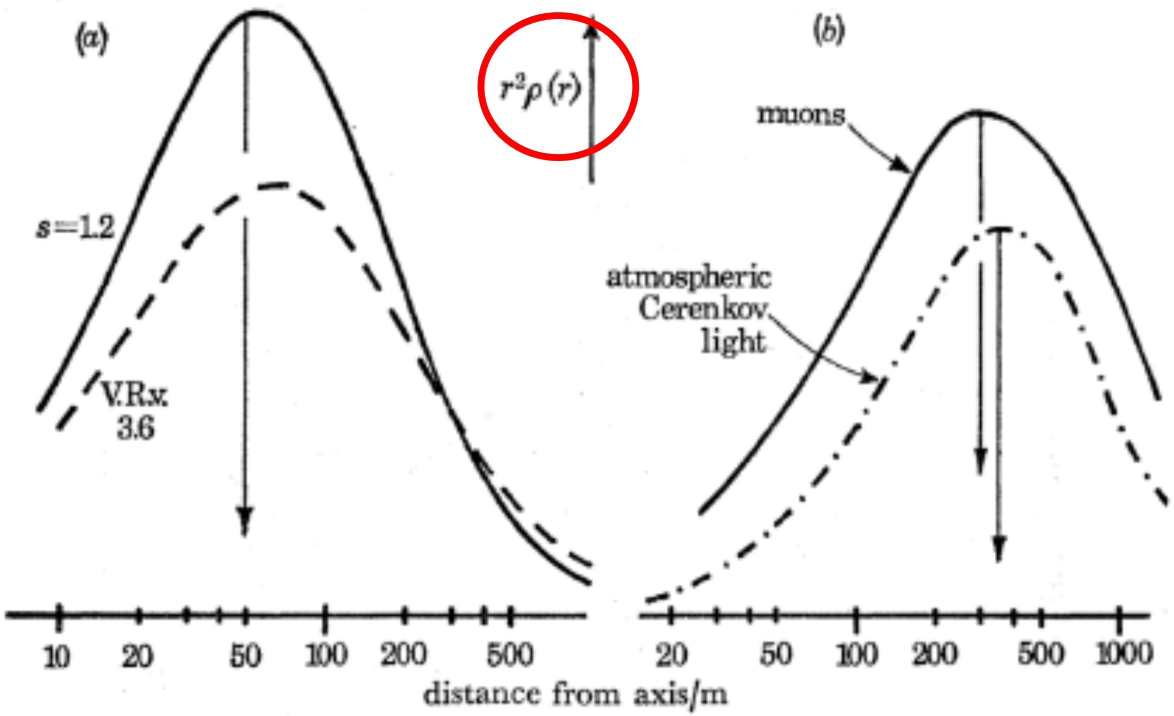


Figure 1: Lateral distribution of different shower components, to show the extrapolation required in estimating total number of particles. Left: Electron component at altitude of Volcano Ranch drawn for two shapes of structure functions. Right: Muons and atmospheric Cherenkov photons, having their main contribution near 300 m from the axis. Extracted from [Hillas, 1975].

Measurements using scintillators (VR) and water-Cherenkov detectors (HP) enabled shower-to-shower differences in the LDFs to be measured

At 10^{17} eV, the rms variation in N is ~70 %, while at 950 m the rms variation of a water-Cherenkov signal is only ~6%

As arrays became larger and larger, detectors spacing had to be increased to several Molière Units, because of cost

In early days at Haverah Park, $E_{100} = K \int_{100}^{1000} r^{-n}\, dr$ (energy flow)

$$E_{primary} \sim 150 \times E_{100}$$

But variation in 'n' from shower-to-shower, and with energy, was a problem

- **In general, except for close-packed arrays of detectors, it is impossible to measure the lateral distribution function on an event-by-event basis**

Hillas (1969) analysed 50 events, *recorded using the Haverah Park array of the time – a star-shaped geometry* – using power-law lateral-distribution functions, differing by 0.6 (consistent with observations)

For the early Haverah Park geometry,

Hillas found that the fluctuation in the signal at 500 m was less than 12%

For E_{100} , with the same values of the power law, differences were typically around 70%

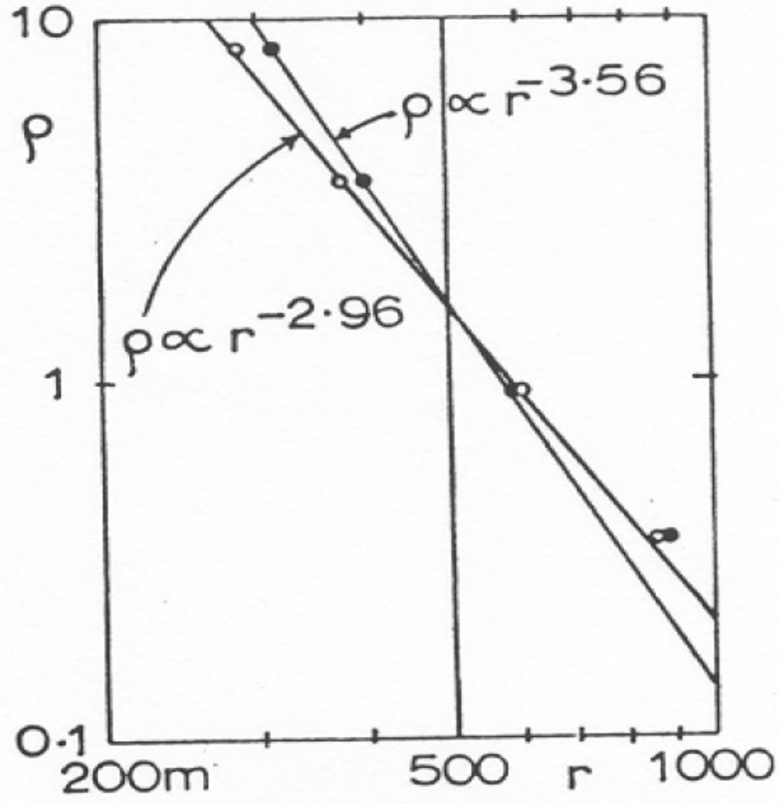


Fig. 2: Effect of change of assumed structure function in analysis of a shower.

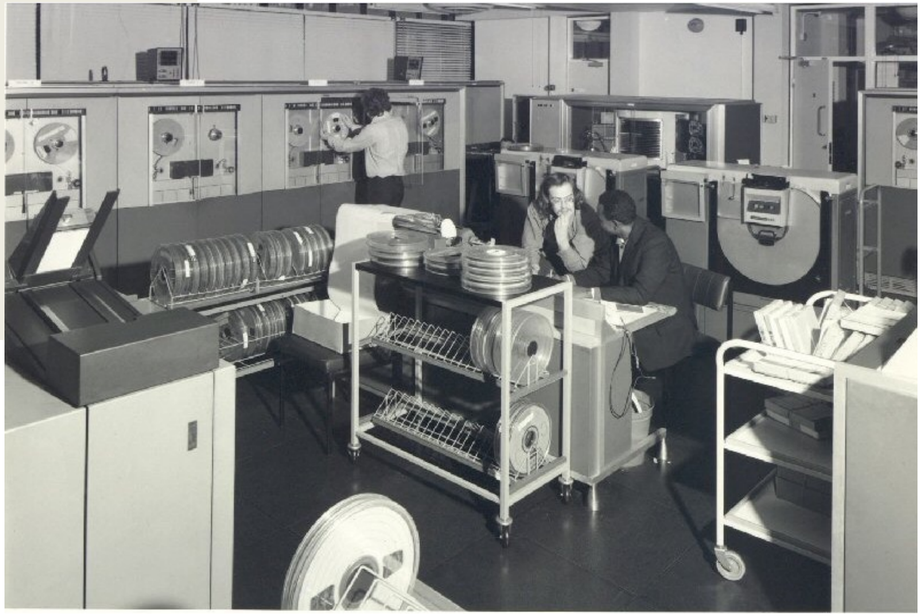
Hillas 1971

At Haverah Park, the surrogate of ρ(500) was first adopted for the 'Engineering Array'

ρ(600) later chosen for the hexagonal geometry of the final array where the average spacing was ~ 1 km.

An educated guess as detailed simulations were not practical:

KDF9 computer: 4.7 tonnes: 192k bytes of memory



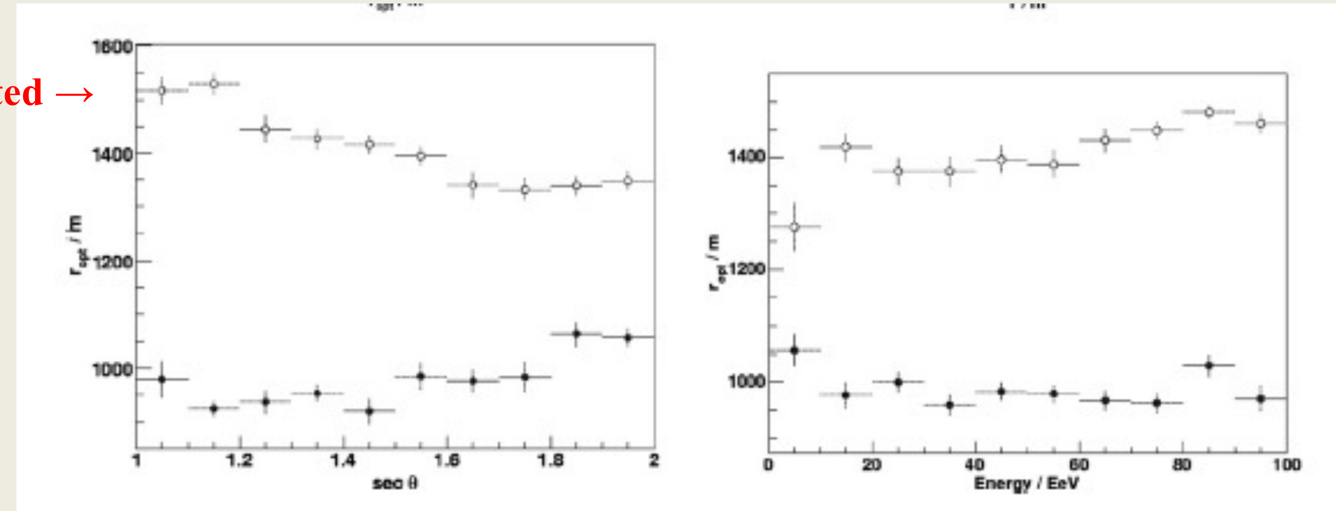
Detailed study for Auger Observatory (Newton, Knapp and Watson 2007)

LDF	r_{opt}/m, mean	r_{opt}/m, RMS	$\Delta S(1000) = \frac{S(1000)_{LDF}}{S(1000)_{NKG}}$
Power law	960	110	1.045 ± 0.001
'Haverah Park'	940	100	0.986 ± 0.001
'NKG' type	970	110	1.00

Difference between optimum values for various ldfs (940 – 970 m) typically shows a spread in S(r) smaller than that at 1000 m of ~2%. So using 100m rather than smaller value not very important

Very little dependence on zenith angle or energy

Saturated →



Dependence of r_{opt} on detector spacing?

- For triangular geometry: ~2/3 of spacing is appropriate choice for r_{opt}
- Used (and checked) for 750 m array of Auger Observatory
- Used (but not checked) by TA for square array
- No obvious relation for HP geometry used in Hillas's seminal work

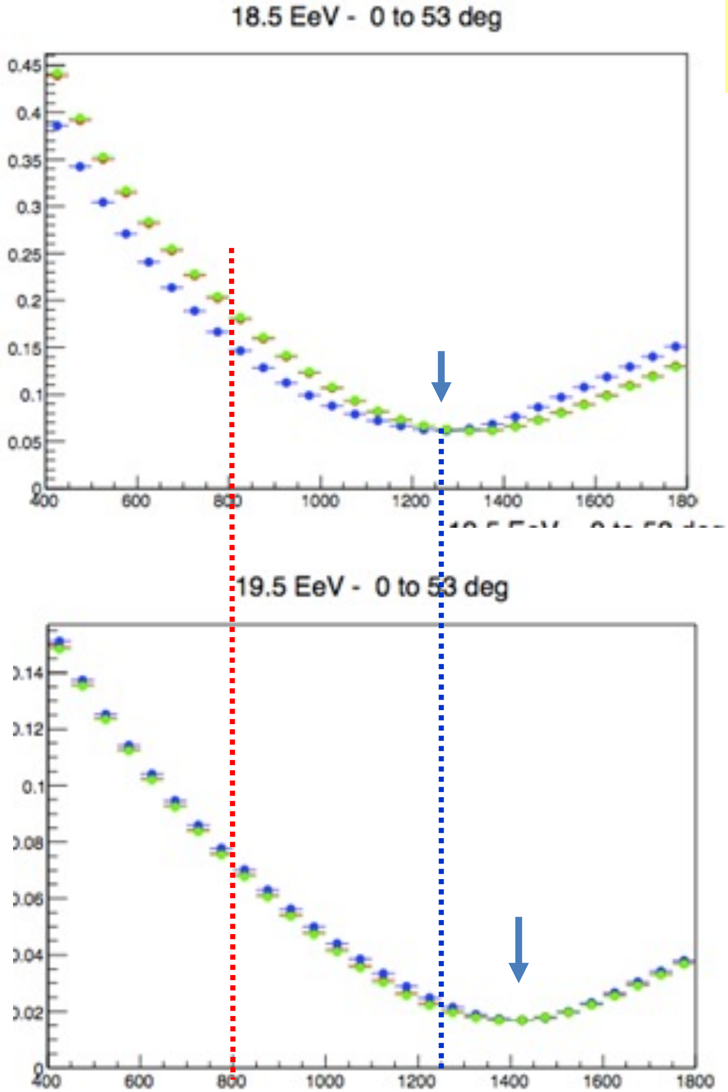
Does the layout of the detectors have an influence on the r_{opt} to be used?

Auger: Triangular grid 1500 m
Telescope Array: Square grid 1200 m

Simulations using TA array with Water-Cherenkov detectors – for two energies and range of angles

σ/S

σ/S

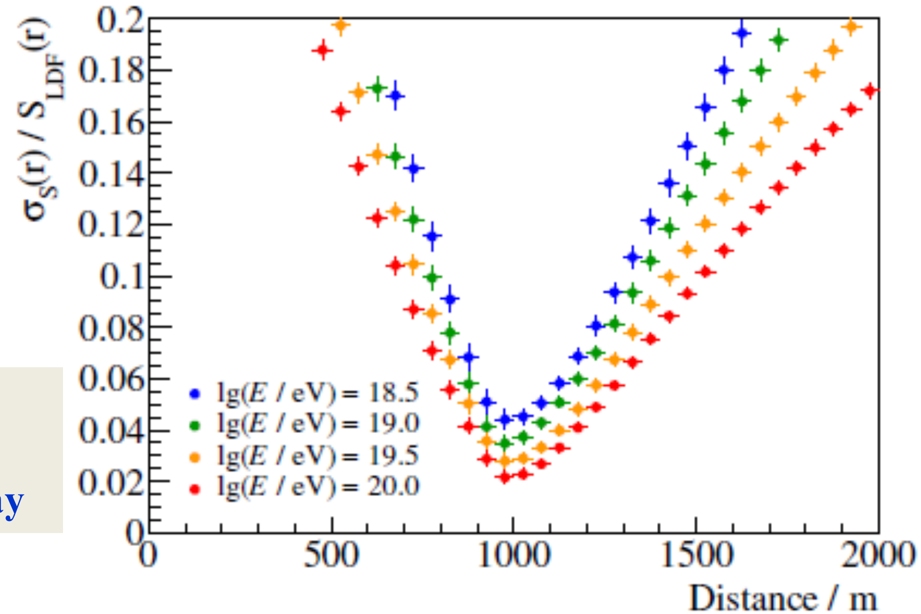


Green – no saturated stations
Blue – saturated stations
Red – all

σ/S is larger at 800 m than at r_{opt}

log E = 18.5: 7% vs ~20%   19.5: 2% vs ~7%

Much smaller effects with triangular array



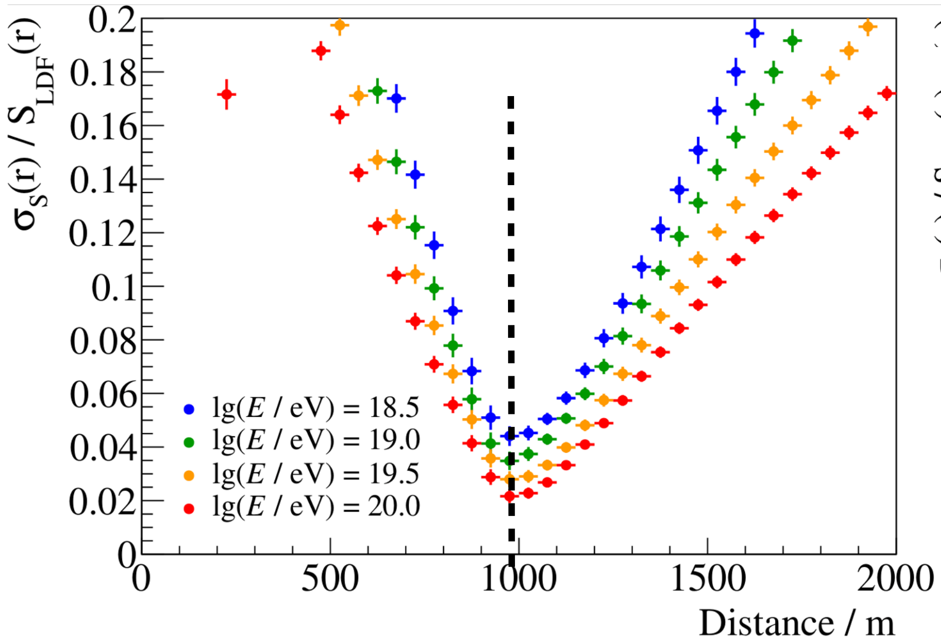
Comparison of results for Triangular and Square grids

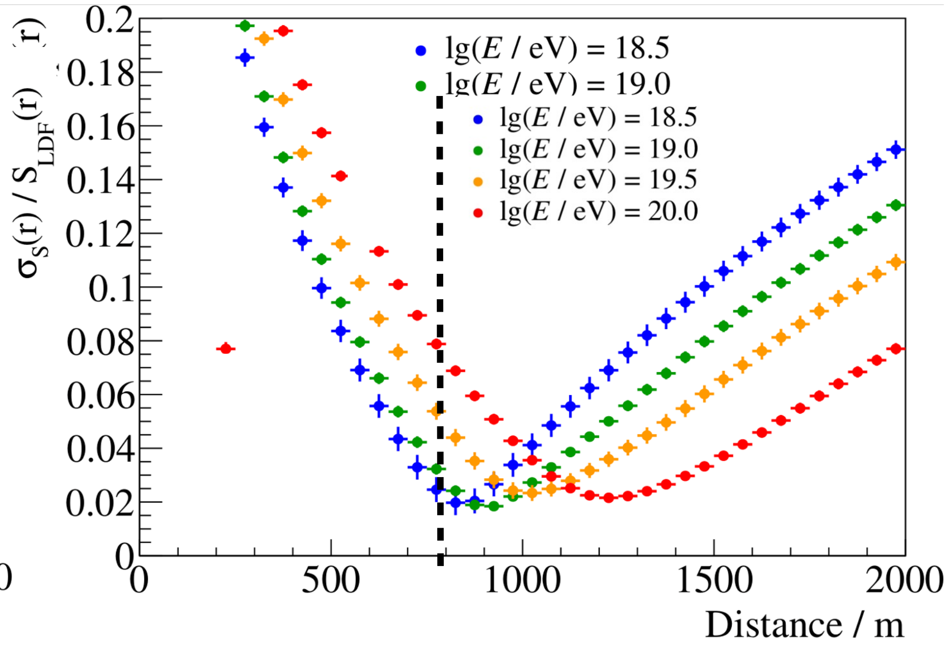
QGSJet-II.04
Proton

$\theta = 0°$

WCD - Triangular grid – 1500 m
Auger-NKG LDF

SSD - Square grid – 1200 m
AGASA LDF





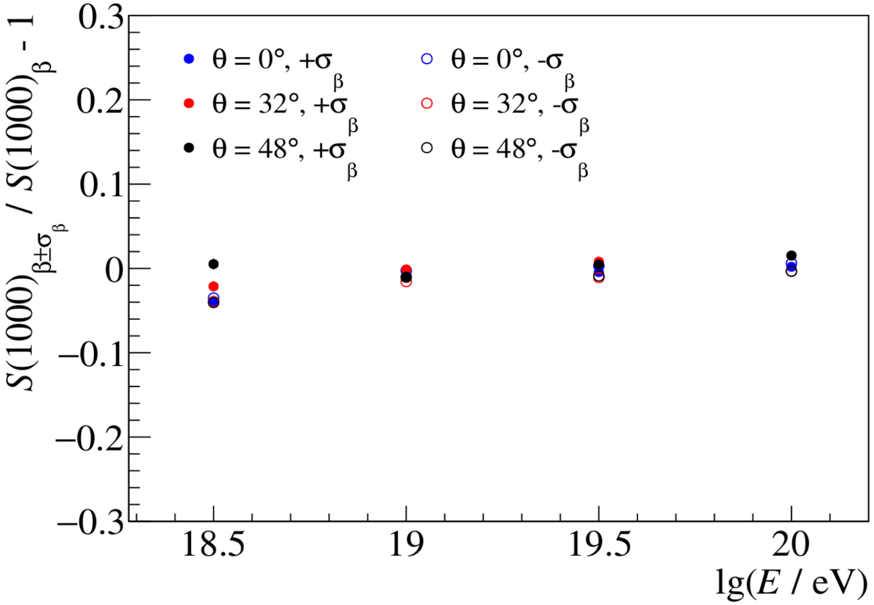
Fluctuations of S(r_{opt})

Fluctuations in S(1000) are biased because of underlying differences in β, the LDF parameter.
Biases stronger, and are asymmetric, for scintillators on square grid

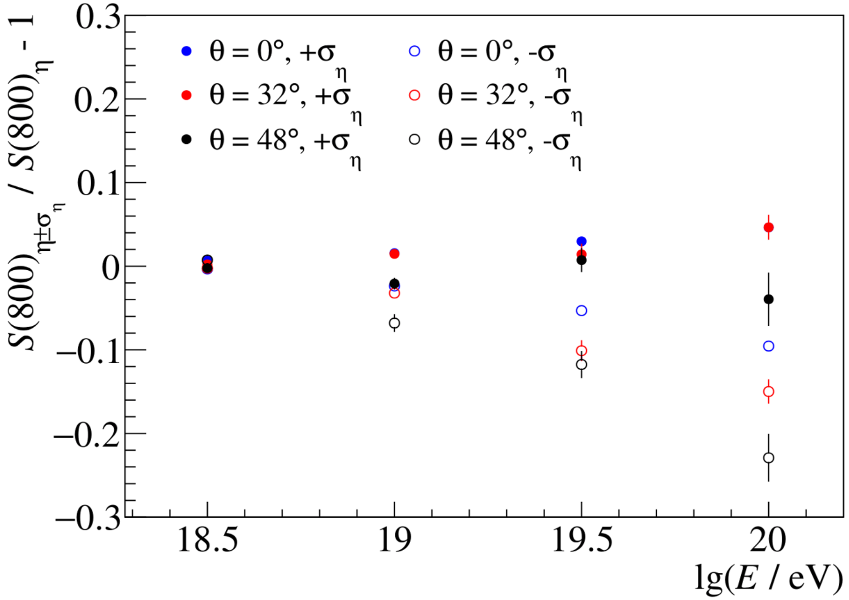
$\theta = 0^{\circ}$

QGSJet-II.04
Proton

WCD - Triangular grid – 1500 m
Auger-NKG LDF



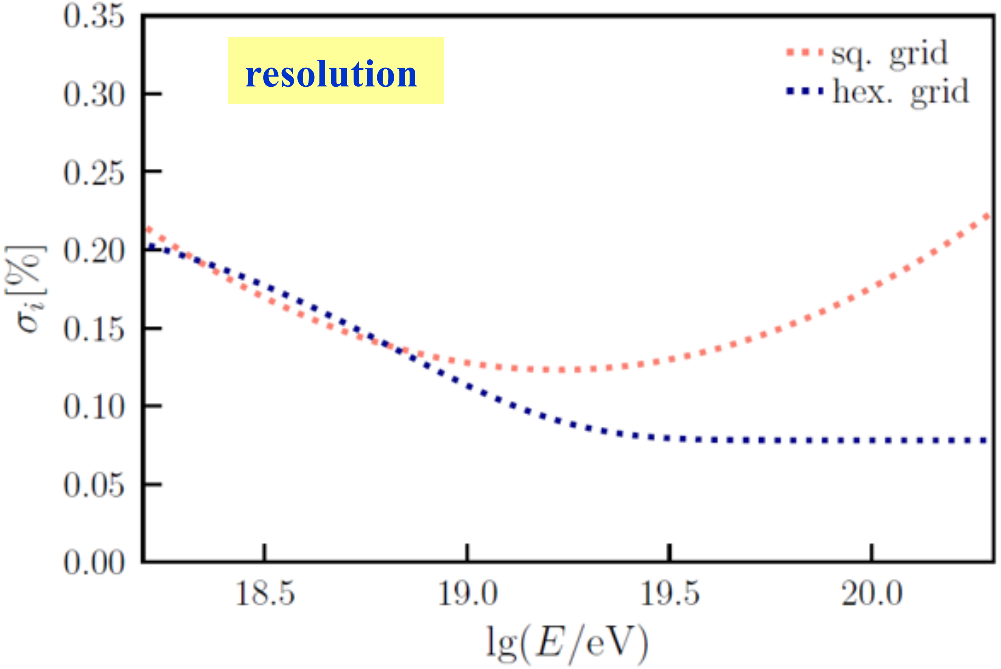
SSD - Square grid – 1200 m
AGASA LDF

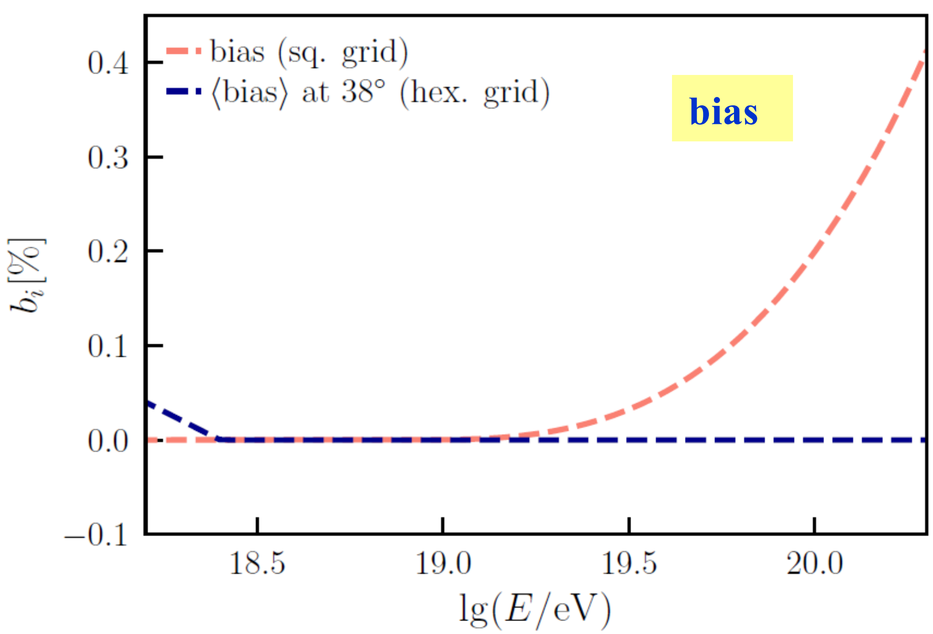


Summary of Resolution and Bias

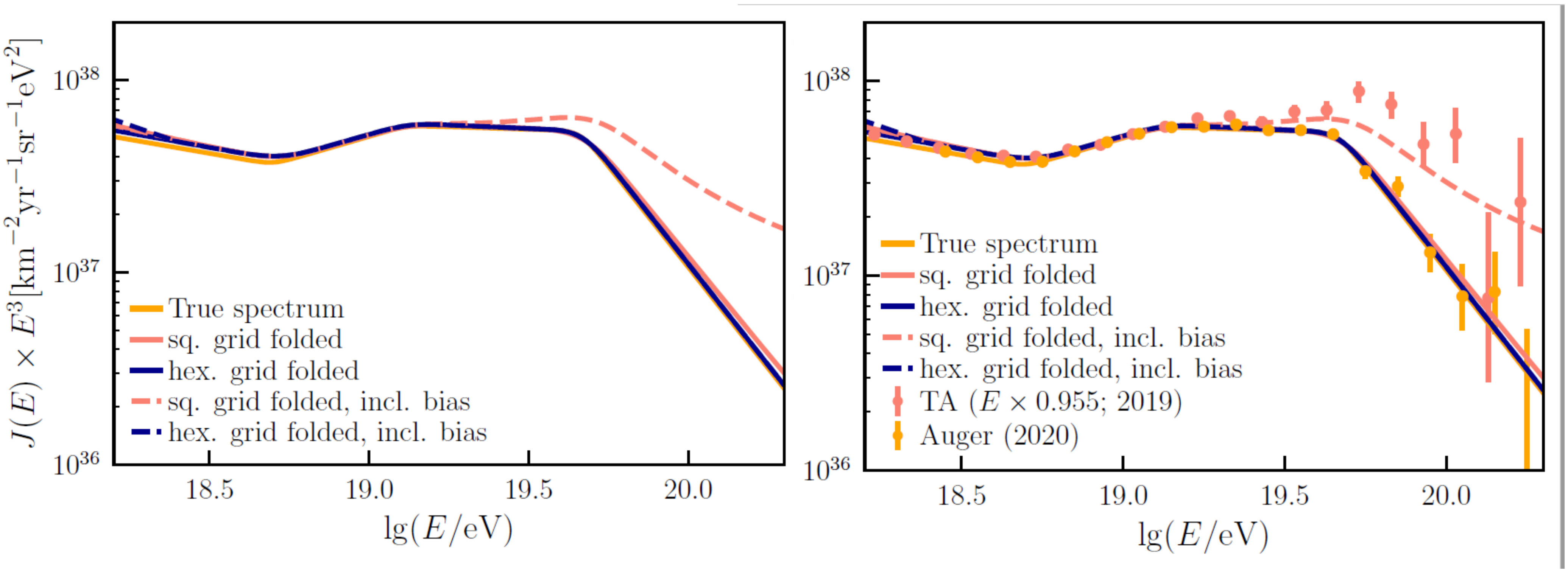
Triangular Grid: Auger: 1500 m array – (*PRD 102, 062005 (2020)*)

Square Grid: Telescope Array: 1200 m square array (our estimates)





Impact on the spectrum



Take home messages:

- **Layout of an array has an impact on r_{opt}**
- **Difference between triangular and square array is important**
- **r_{opt} dependencies should be investigated for planned geometries**
- **Desirable that r_{opt} does not depend on energy or zenith angle**
- **Energy dependence in case of TA geometry possibly contributes to TA/Auger differences in Spectrum**

Active discussion now underway within Auger/TA WG on spectrum

- **But, WHY is there this dependence?**