Optimal reference distance and its implication on the (Auger) Cosmic Rays Energy Spectrum

O. Deligny, I. Lhenry-Yvon, Q. Luce, M. Roth, D. Schmidt, A.A. Watson

IAP-HEU Groups Seminar - 25th May 2023

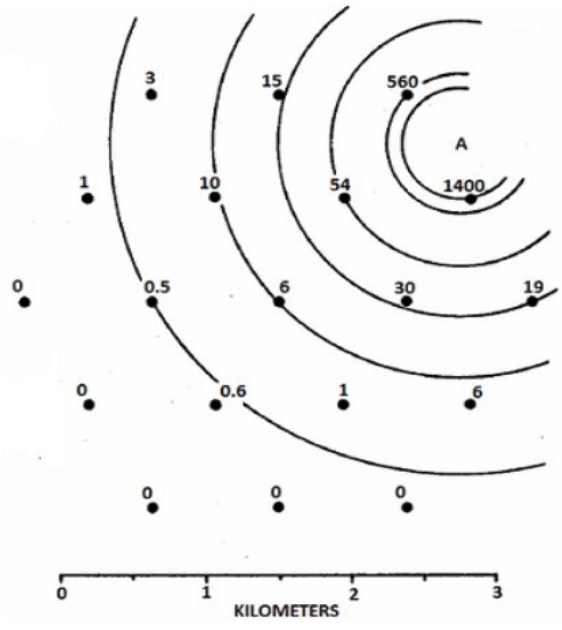
A story about the **distance** that wanted to be **optimal** to not affect the **energy spectrum** of Ultra-High Energy Cosmic Rays,

BUT...

On-going analysis, final results expected for the ICRC23 (D.Schmidt)

Prelude: A bit of history

Volcano Ranch

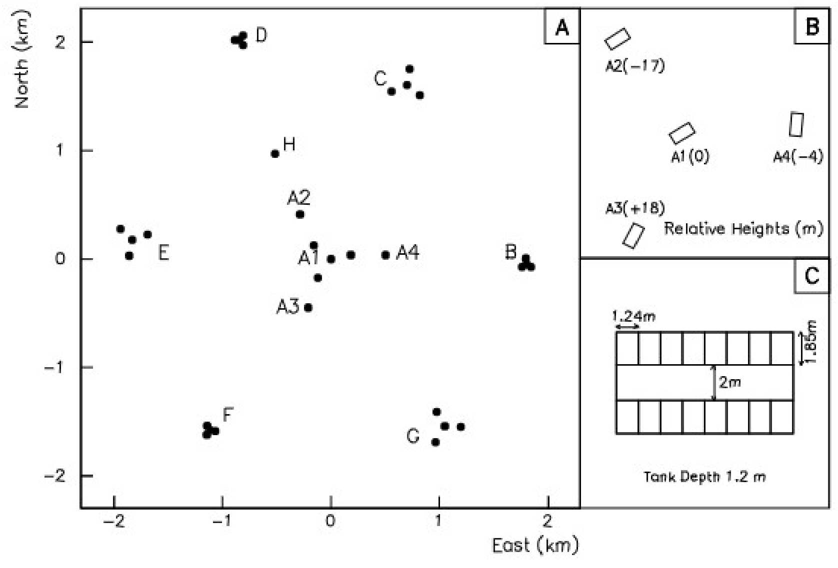


Observation of ultra-high energy cosmic rays using **ground based experiments**

In 1970s, two main **surface detectors** projects:

- **Volcano Ranch** in New Mexico
  scintillators,~8.1 km², spacing 147 m
- **Haverah Park** in Scotland
  water-Cherenkov detectors, ~12 km², infill spacing 150 m

Haverah Park (Scotland)



How to reconstruct the **number of particles** (i.e. energy of CR) with a spacing between two detectors **~1.5 Molière radius**?

1 Molière radius = radius containing 90% of the number of particles in a shower

VR: Linsley (1977)
HP: Ave et al. (2003)

Main protagonist: optimal distance

Early days of Haverah Park experiment:

$$E_{CR} \propto \int_{100}^{1000} r^{-n} \mathrm{d}r$$

Lateral Distribution Function (LDF) = description of the lateral profile of shower

BUT: shower to shower variation and dependency with energy for the exponent *n*

If $\Delta n = 0.6 \rightarrow \Delta E_{CR} = 70\%$

Event-by-event LDF impossible

Solution: Averaging the LDF

With 50 events of Haverah Park:

$r = 500$ m and $\Delta n = 0.6 \rightarrow \Delta\rho = 12\%$

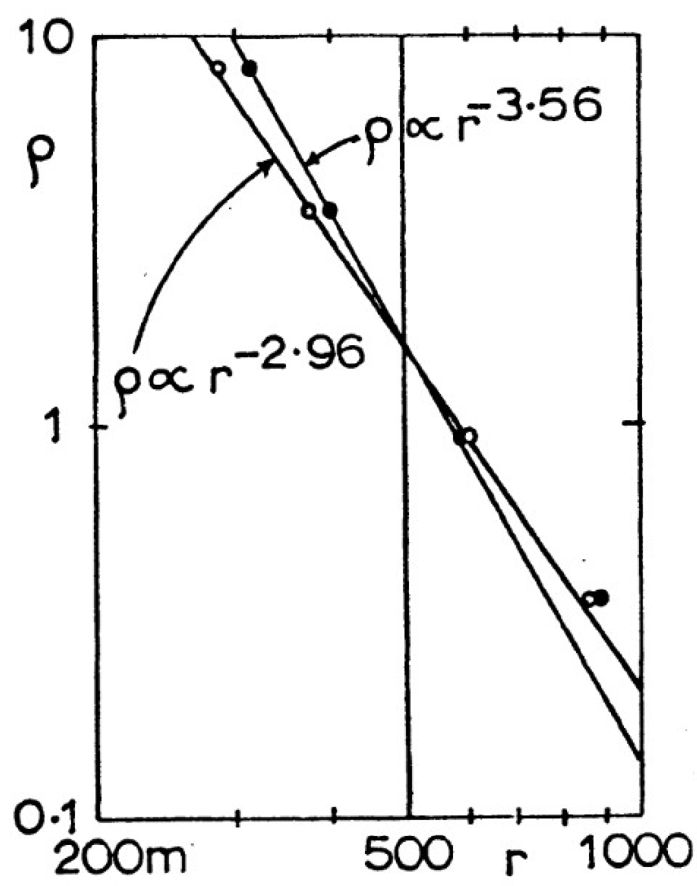


Fig. 2: Effect of change of assumed structure function in analysis of a shower.

Introduction of a **distance** at which the **signal** is extracted as a **proxy for the energy of the cosmic ray = Optimal distance**

Hillas (1971)

Main protagonist: optimal distance

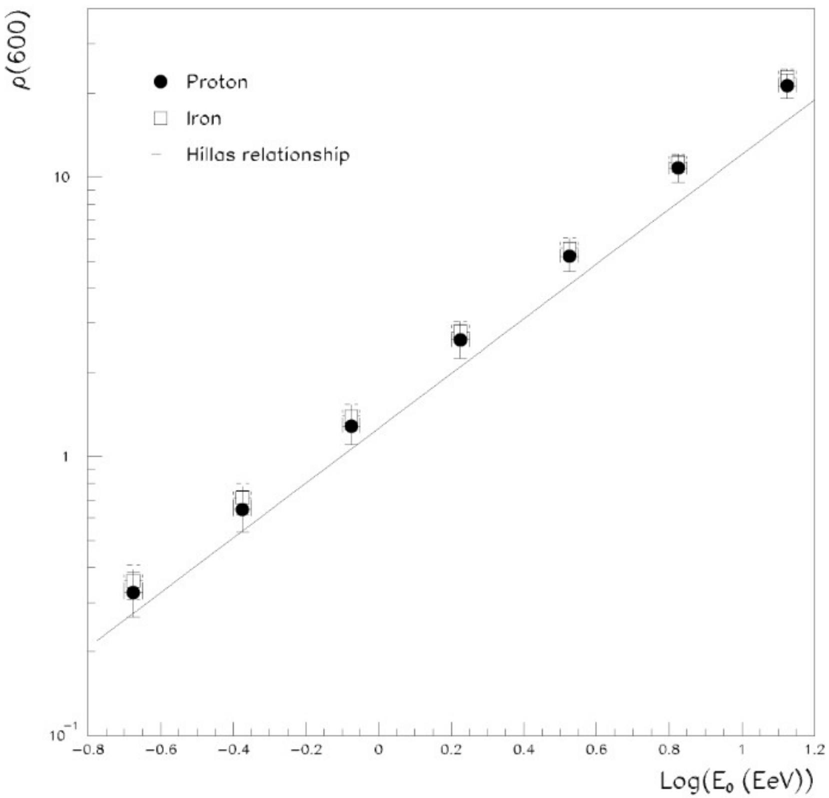


Fig. 2. $\rho(600)$ as function of E_0 for proton and iron showers at $\theta = 26°$, from CORSIKA/QGSJET simulations. Simulation results by Hillas et al. (1971) are plotted as solid line.

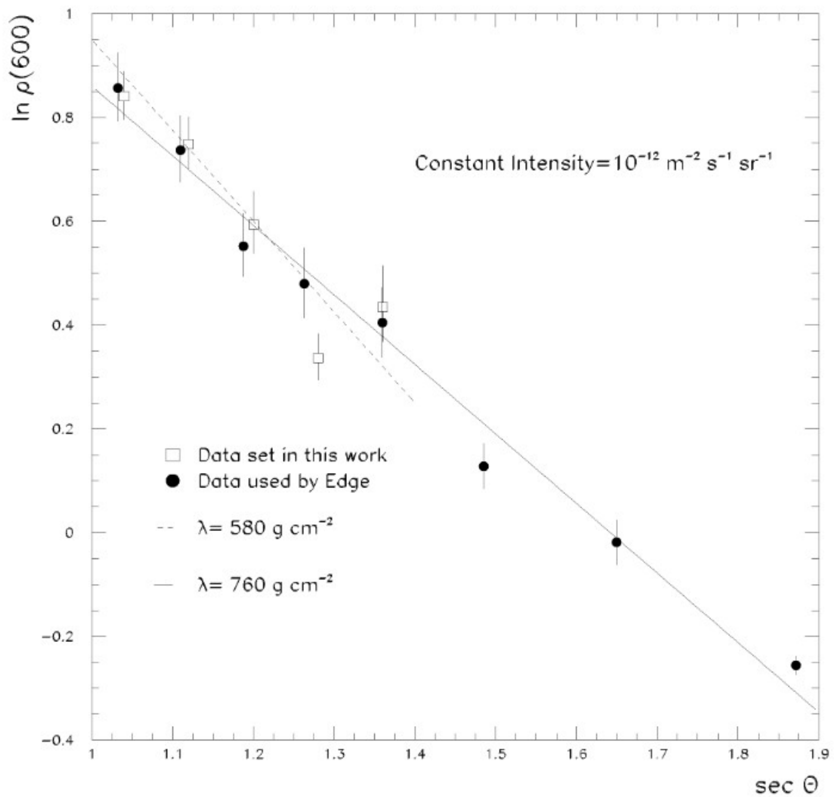


Fig. 3. Attenuation of $\rho(600)$ with zenith angle deduced with the constant intensity cut method. Results by Edge et al. (1973) are compared with our analysis.

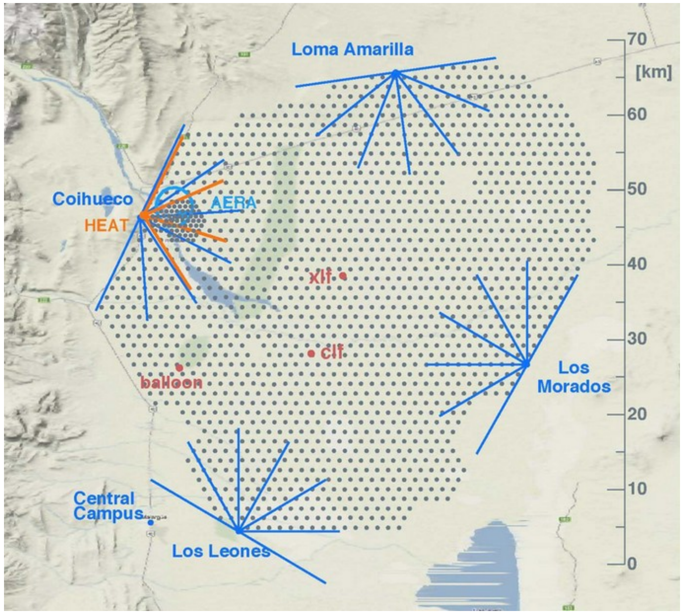
Introduction of a **distance** at which the **signal** is extracted as a **proxy for the energy of the cosmic ray = Optimal distance**

Ave et al. (2011)

Nowadays, two experiments…

Southern hemisphere:

Pierre Auger Observatory (Auger)



Malargüe, Mendoza, Argentina

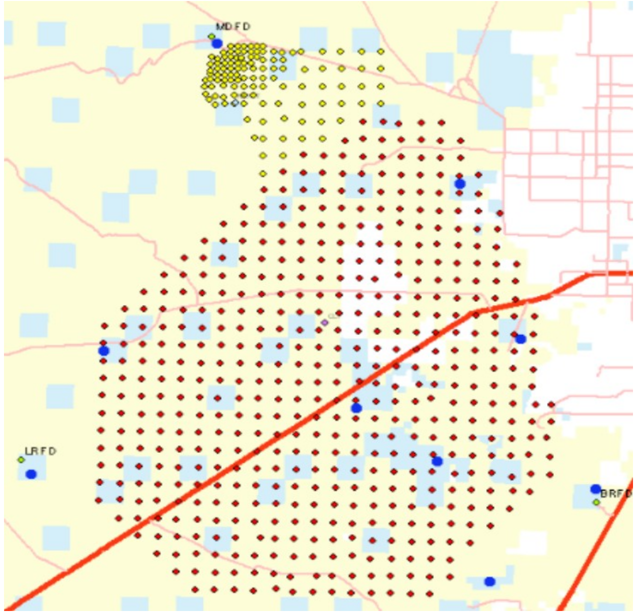
~3000 km²

1660 **water-Cherenkov detectors** (WCD) on a **1500 m - triangular grid**
+ scintillators surface detectors (SSD) on top of each WCD (under deployment)

Overlooked by 4 sites of **fluorescence telescopes** (24+3 telescopes)

Northern hemisphere:

Telescope Array (TA)



Millard County, Utah, USA

~700 km²

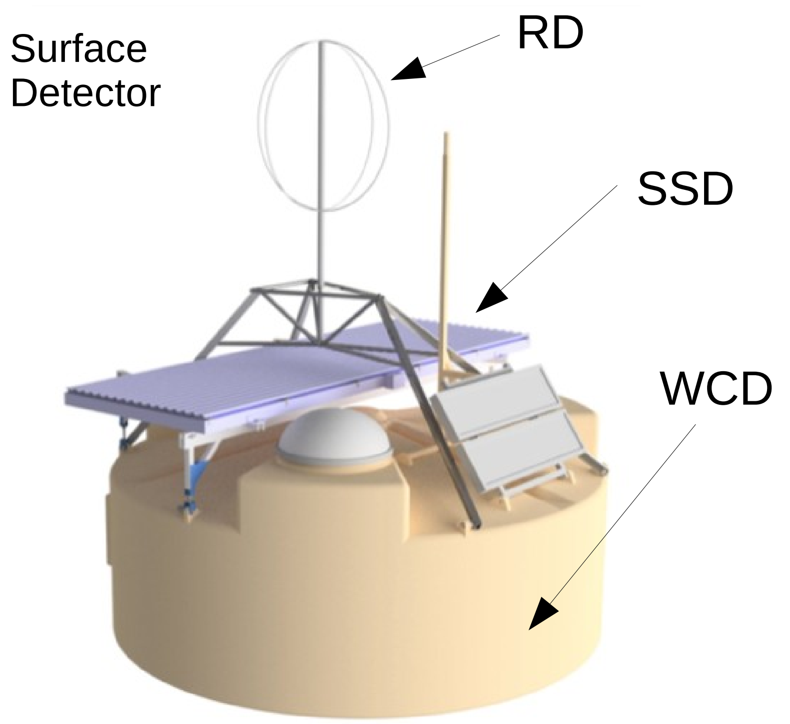
507 **scintillators** on a **1200 m - square grid**

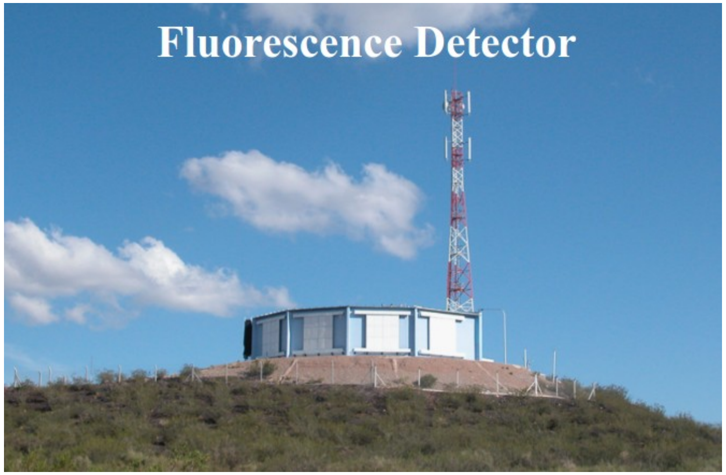
Extension of the surface **x4**

Overlooked by 3 sites of **fluorescence telescopes** (24+3 telescopes)

Nowadays, two experiments…

Pierre Auger Observatory (Auger)





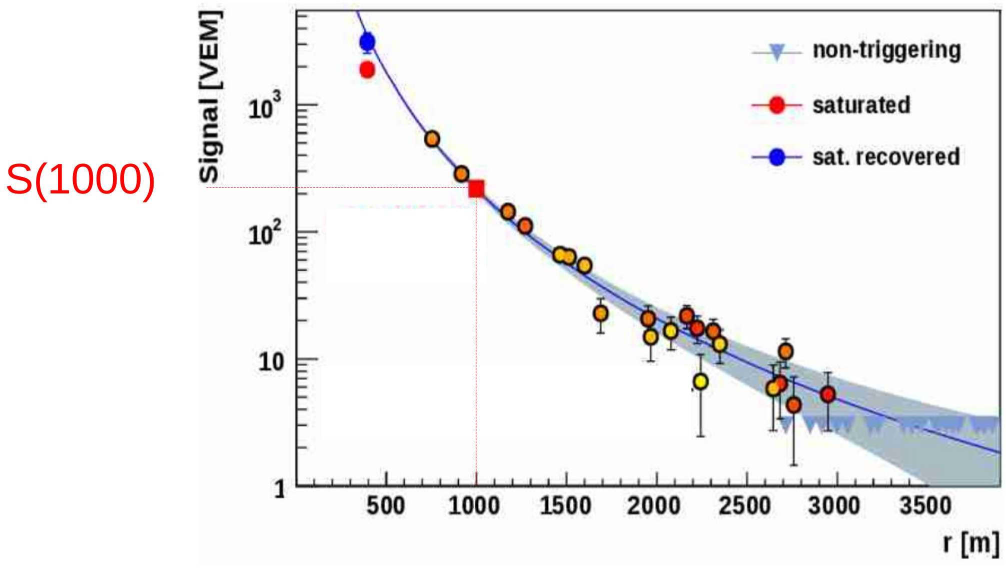
Telescope Array (TA)

Two experiments, **similar** reconstructions…

Pierre Auger Observatory (Auger)

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+r_0}{1000+r_0}\right)^{-\gamma}$$

r_0 = 700 m

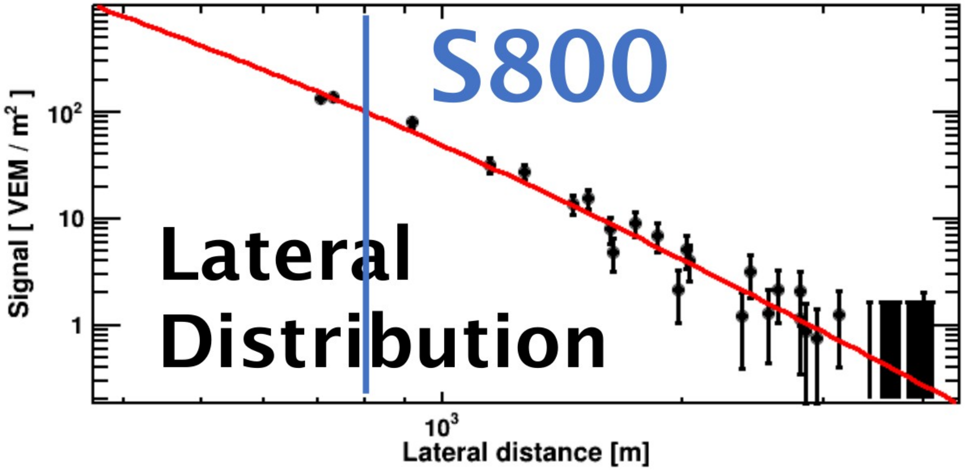


Optimal distance: **1000 m**
(Newton et al. 2007)

Telescope Array (TA)

$$\rho(r) = A\left(\frac{r}{r_0}\right)^{-1.2}\left(1+\frac{r}{r_0}\right)^{-(\eta-1.2)}\left(1+\left(\frac{r}{1000}\right)^2\right)^{-0.6}$$

r_0 = 91.6 m



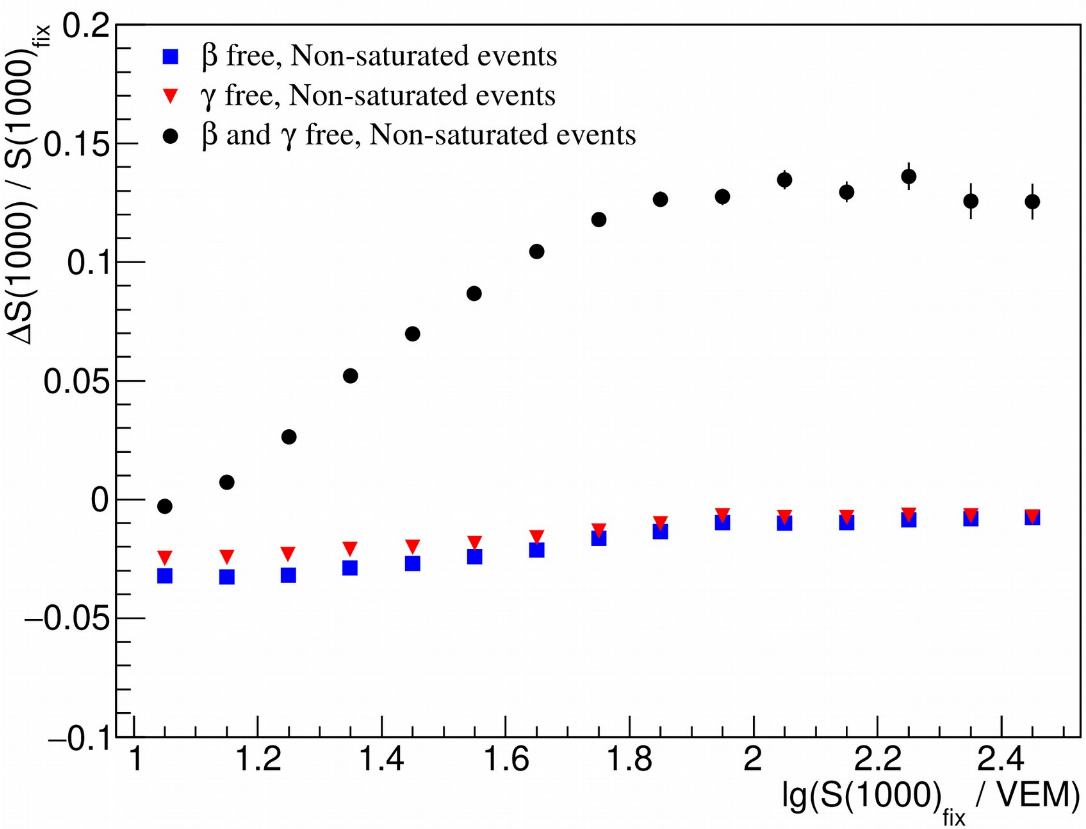
Optimal distance: **800 m**
« distance at which fluctuation between proton and iron are minimals »

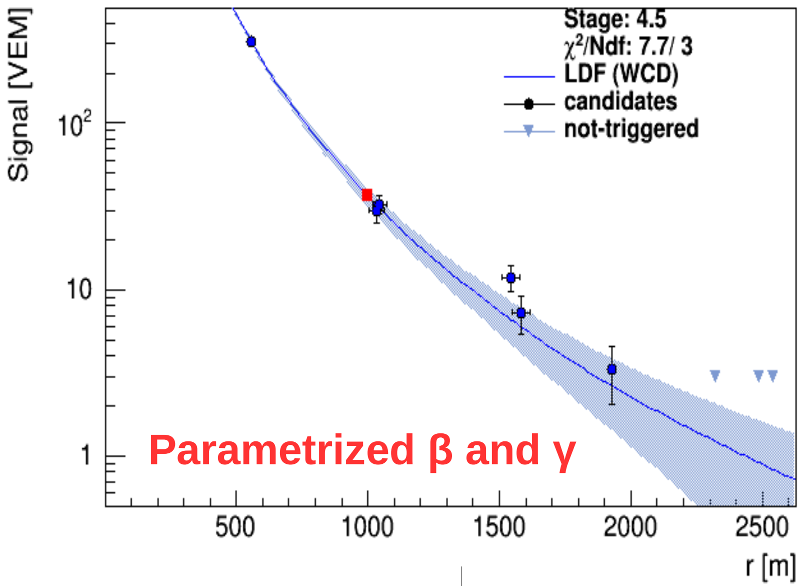
LDF inherited from AGASA experiment (1988)

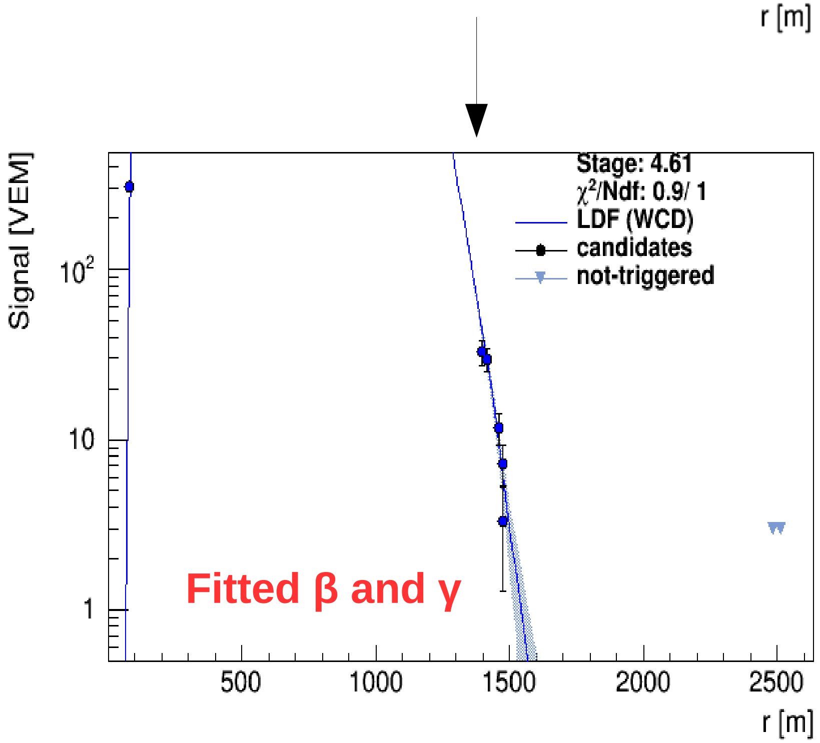
The Pierre Auger Collaboration (2020)
Ivanov et al. (UHECR2018)

On the need of an average LDF

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+r_0}{1000+r_0}\right)^{-\gamma}$$





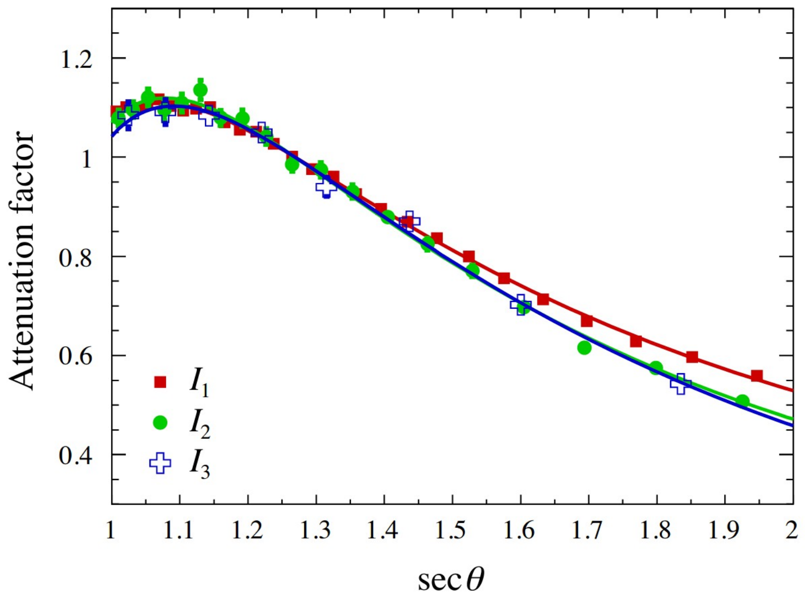


Unphysical solution

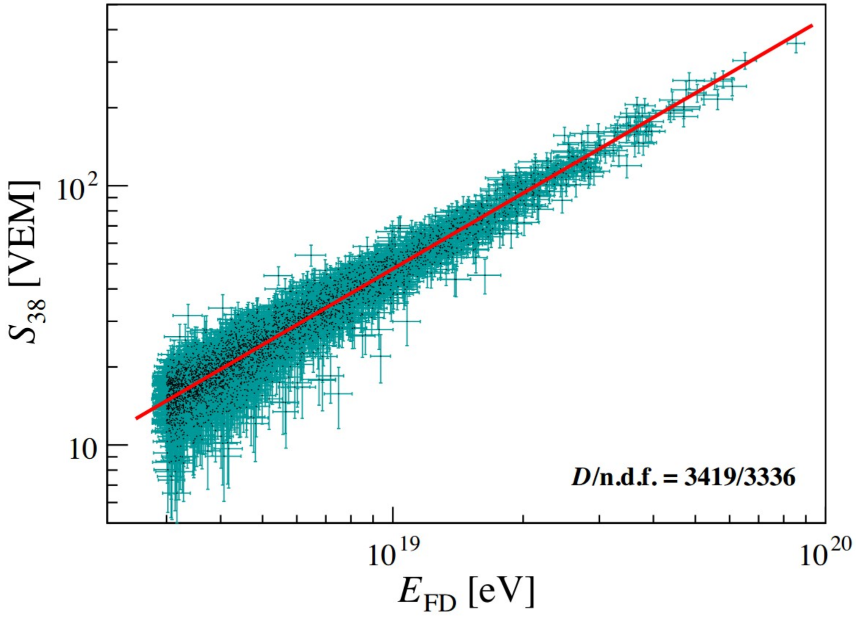
Two experiments, **similar** reconstructions…

Pierre Auger Observatory (Auger)

Correction of the attenuation:

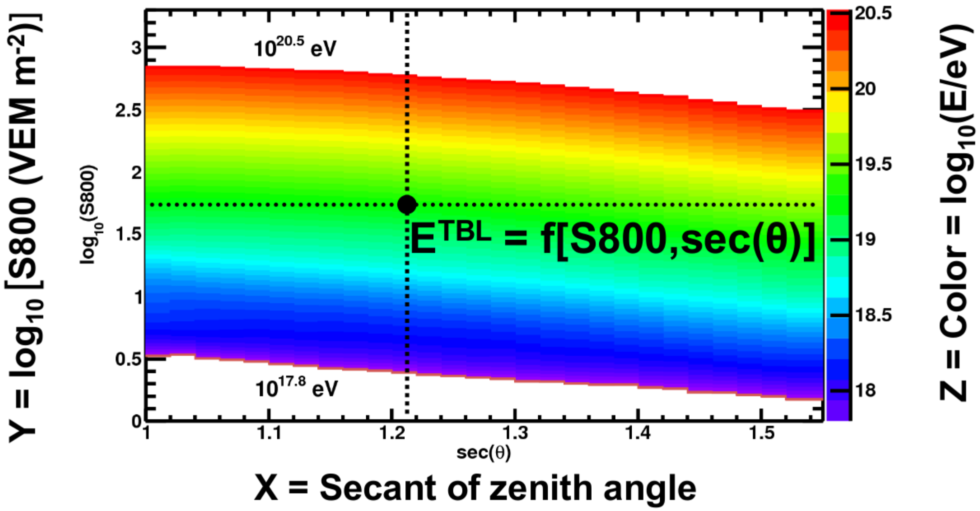


Calibration with hybrid events:

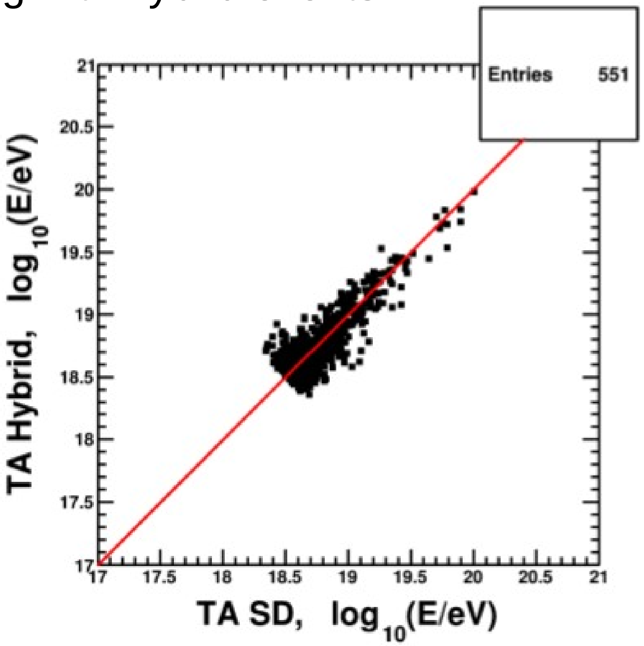


Telescope Array (TA)

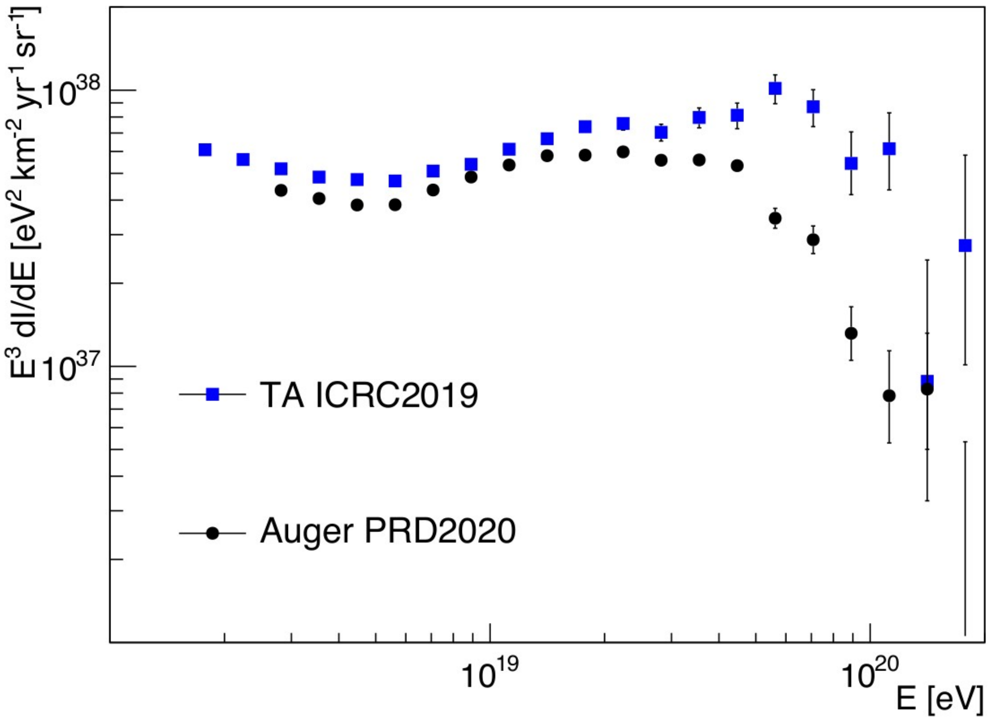
Look-up table from **QGSJet-II.03, protons**

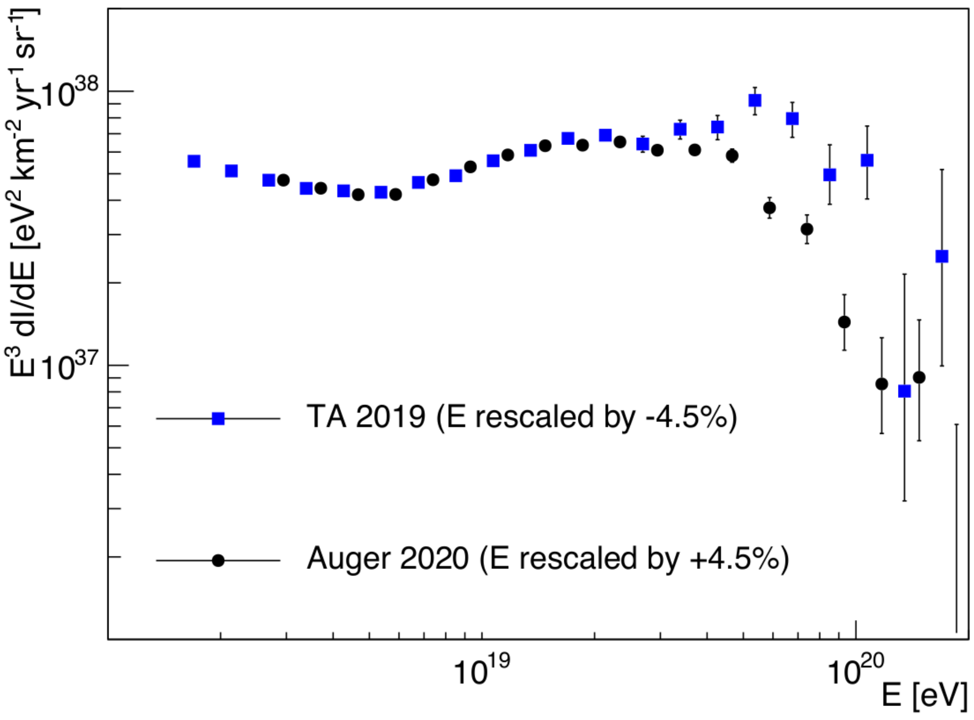


Rescaling with hybrid events:



Two experiments, two spectra?





Discrepancies persist looking at the same **declination band!**

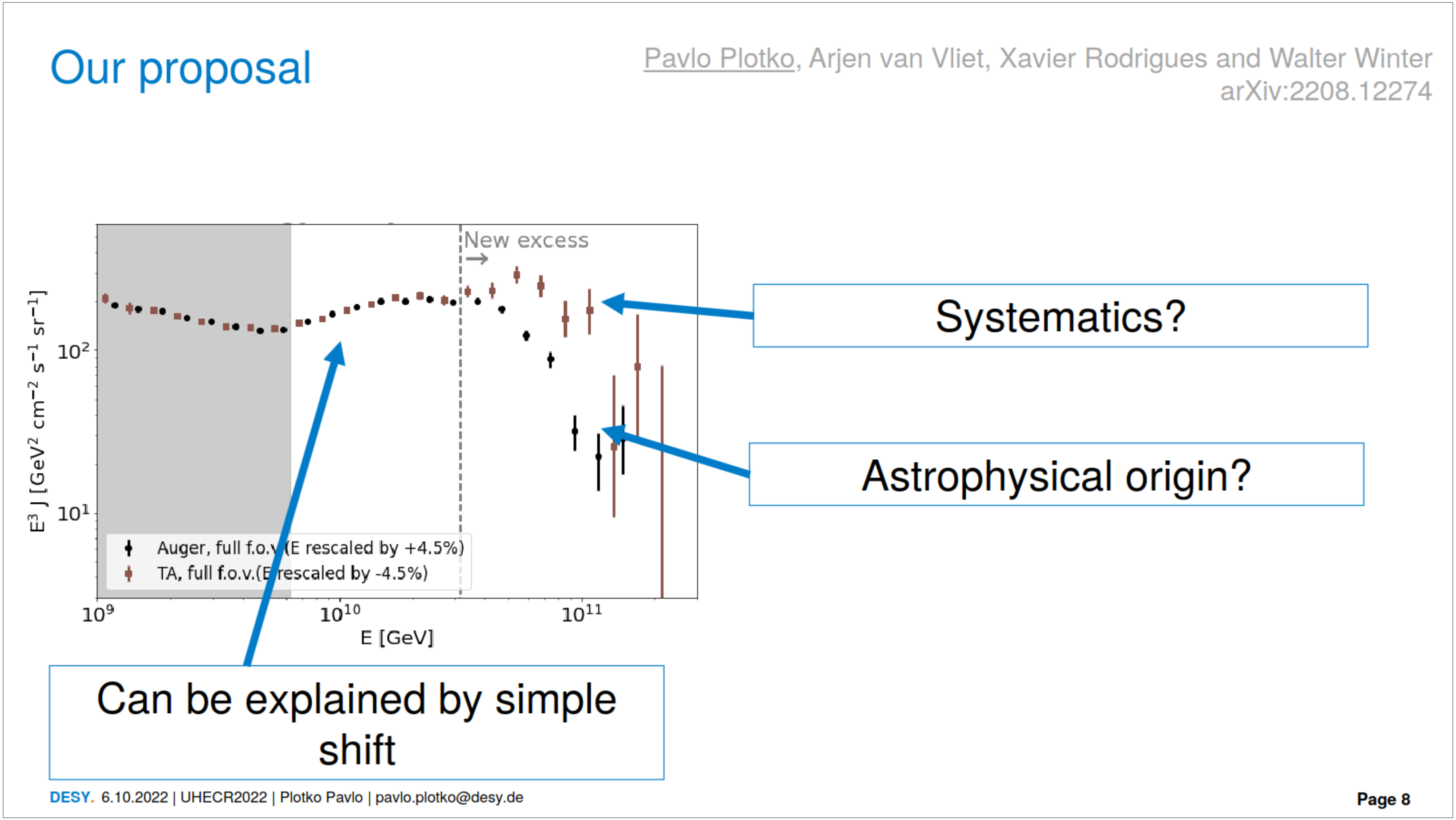
Events on a **square grid** reconstructed using the **LDF from AGASA (1988)**

Misestimation of the estimator of the shower size → impact on the spectrum?

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

UHECR2022…

Presentation from **Pavlo Plotko**



Chapter 1:

Extraction of the optimal distance

From a simulated data set

Optimal distance = distance at which fluctuations due to the unknown true shape of the LDF are **minimals**

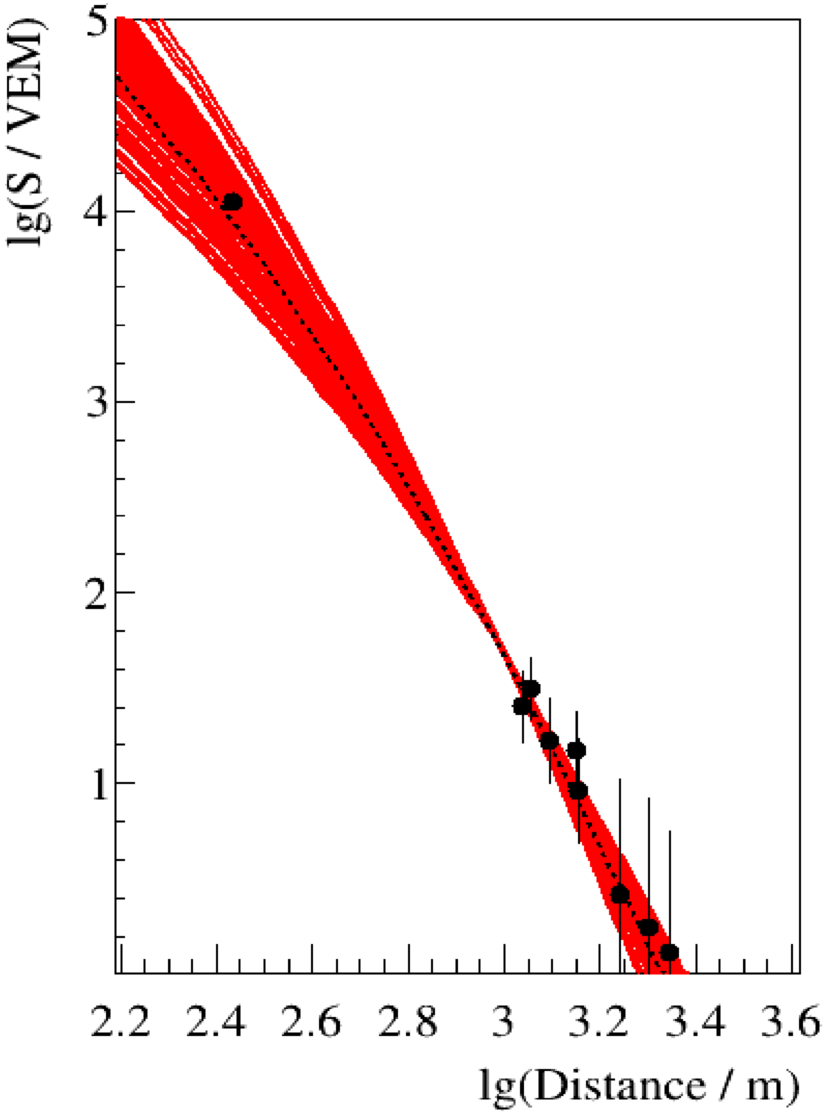
Proton primary
QGSJet-II.04
lg(E / eV) = 18.5 - 20
θ = 0°-60°

mimick TA

Triangular grid – 1500 m
Square grid – 1200 m

Simulations of both **WCD** and **SSD**

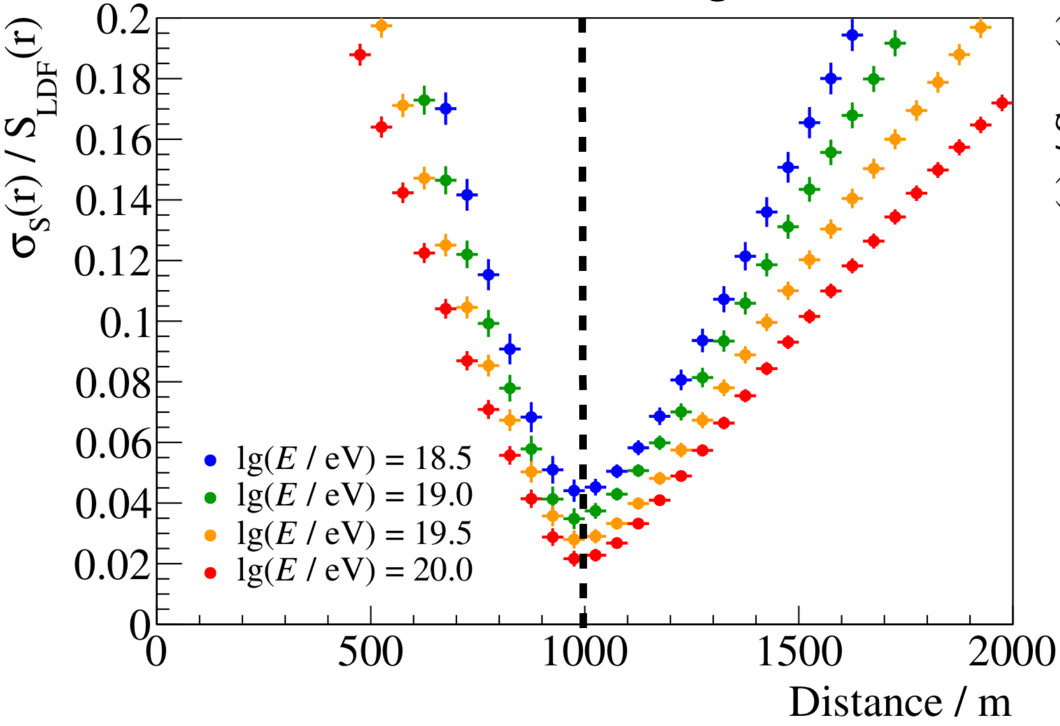
Reconstruction **100 times** an event drawing the logarithmic slope according to a Gaussian distribution



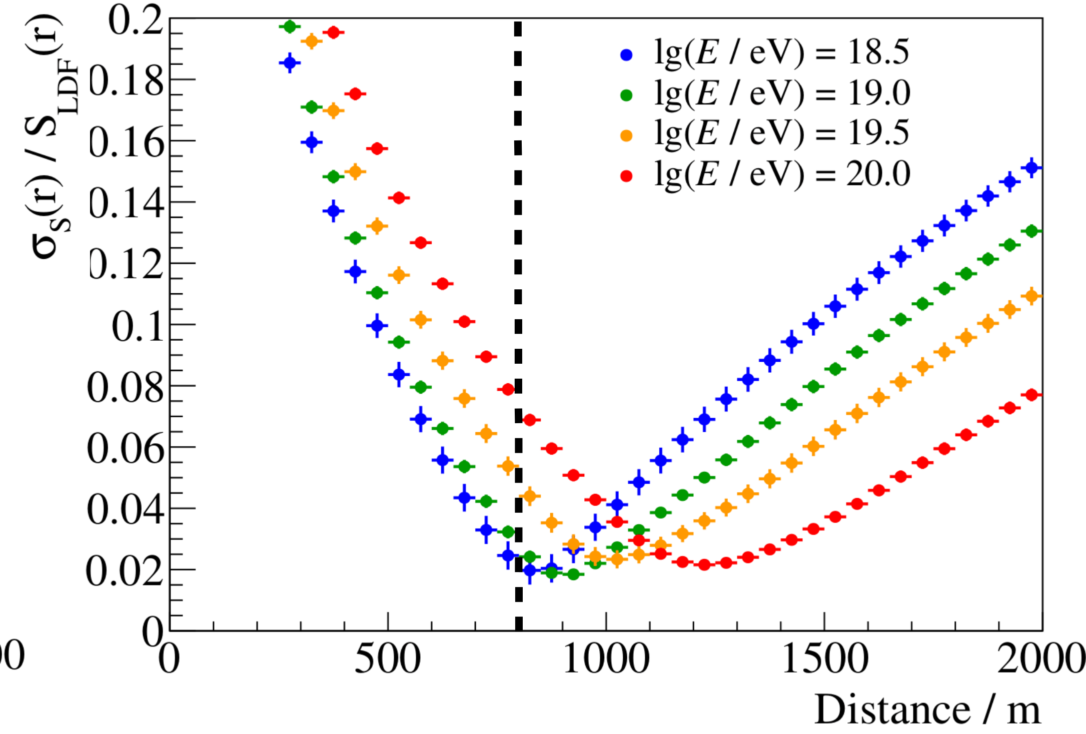
Optimal distance?

QGSJet-II.04
Proton
$\theta = 0^{\circ}$

WCD - Triangular grid – 1500 m
Auger-NKG **LDF**



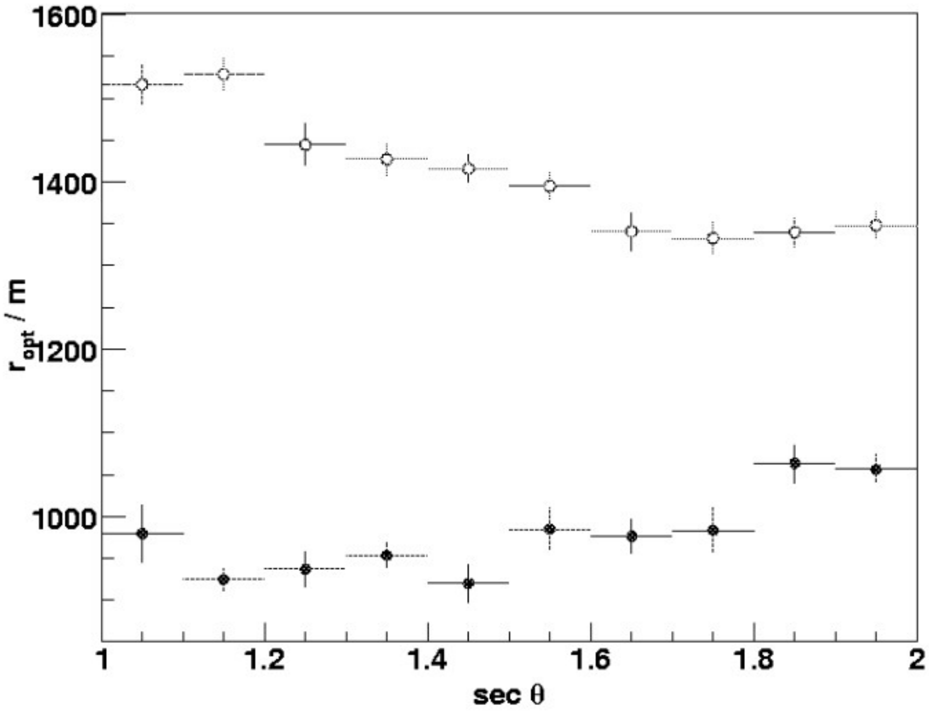
SSD - Square grid – 1200 m
AGASA **LDF**

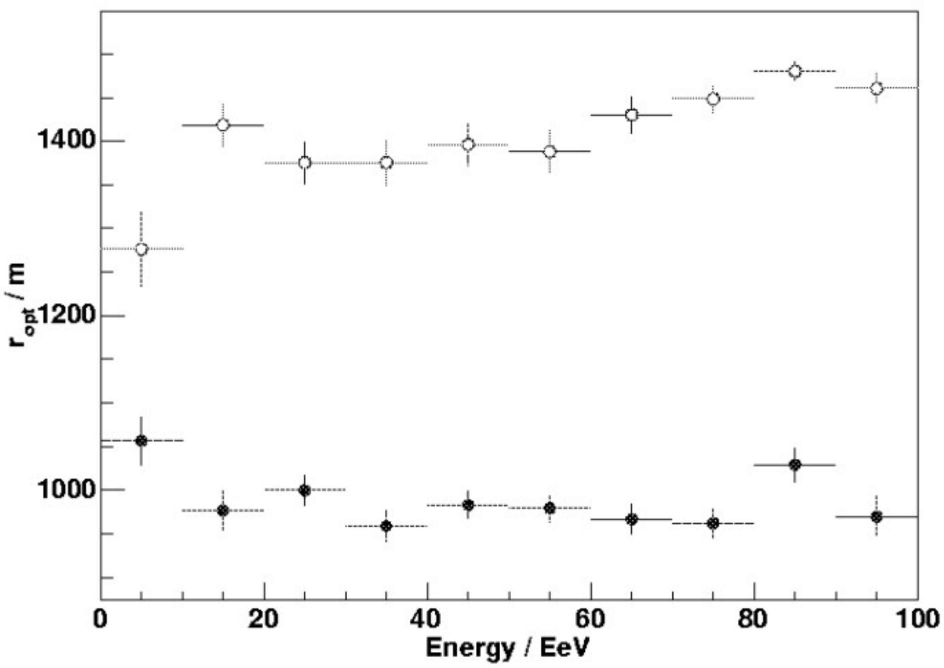


Similar results using **iron primaries** or **EPOS-LHC**

One distance for Auger?…

One distance independent of energy or zenith





- ● Non-saturated events
- ○ Saturated events

Newton et al. (2007)

… but several for TA or AGASA?

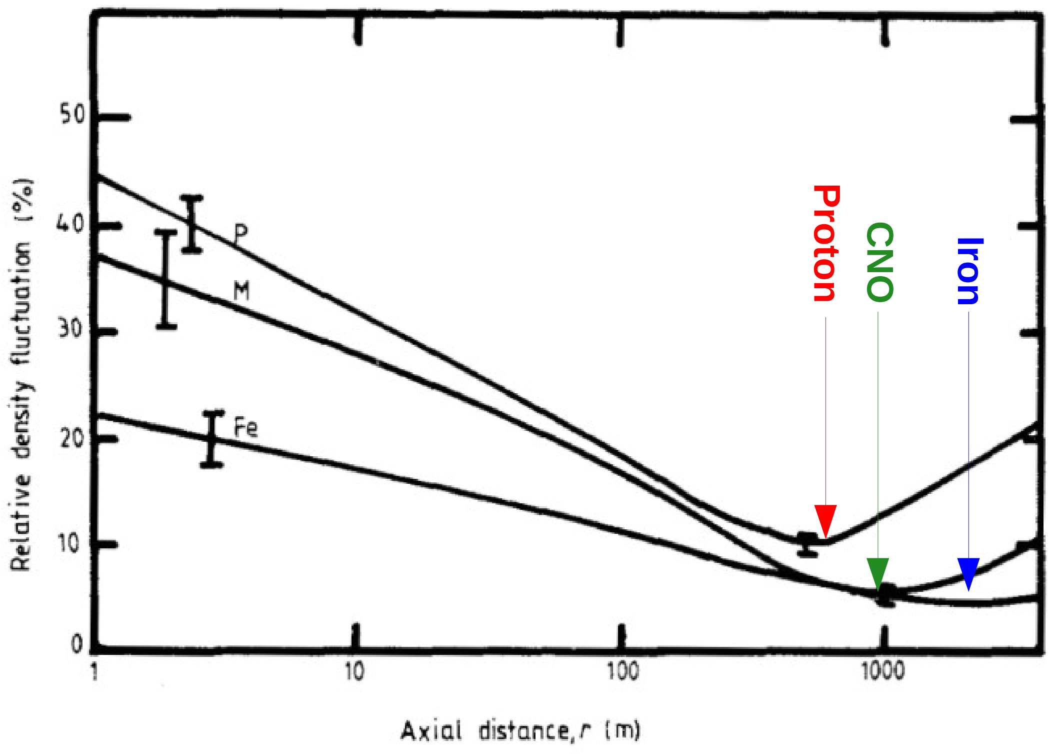


Figure 9. Relative density fluctuation for different compositions. P, proton; M, CNO, Fe, iron (10^{17} eV, sec $\theta = 1.0$).

« Figure 9 shows that the optimum distances (where minimum fluctuation is attained) for different compositions are between 600 and 1200 m »

« **This optimum distance varies with energy** »

Dai et al. (1988)

What could cause the zenith/energy dependency?

Energy dependency of the optimal distance could be due to ?

- **saturation effect**
- **geometry of the array**: square vs triangular
- **parametrization of the LDF**: does it imply differences between SSD/WCD?

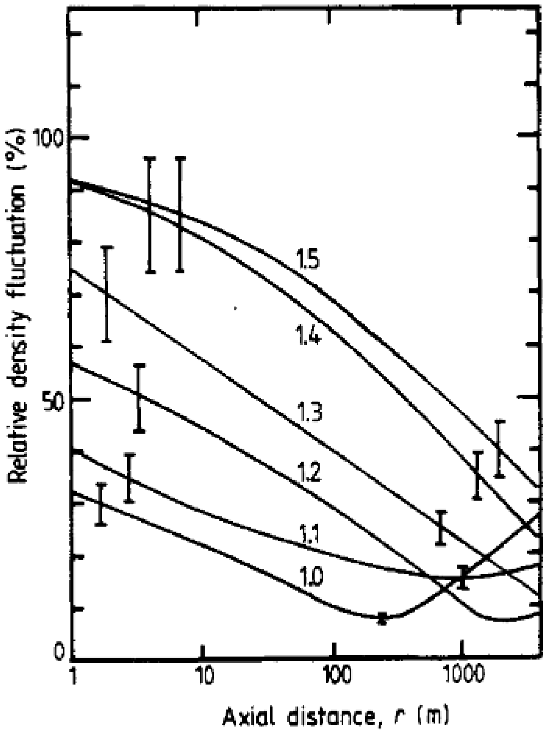


Figure 6. Same as figure 5, but for 10^{18} eV primary.

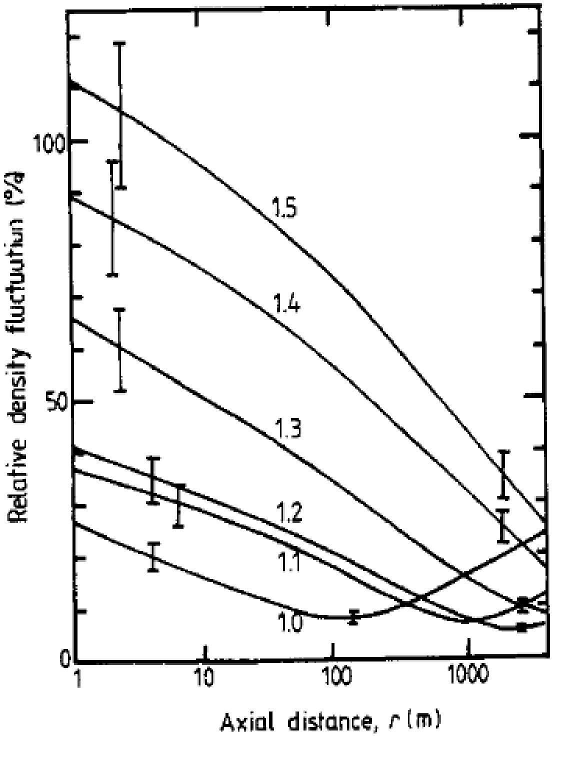
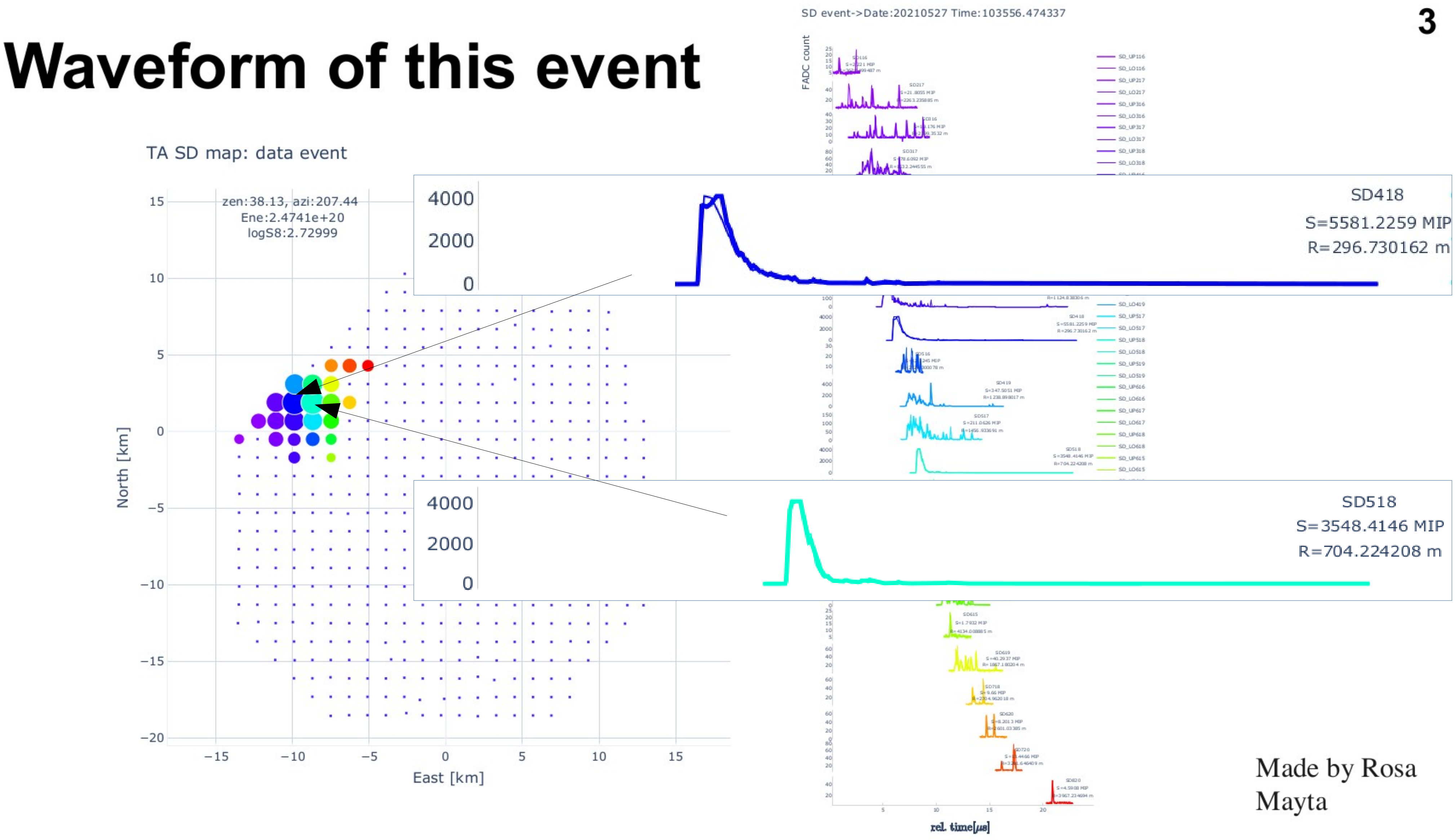


Figure 7. Same as figure 5, but for 10^{19} eV primary.

Dai et al. (1988)

What is saturation?

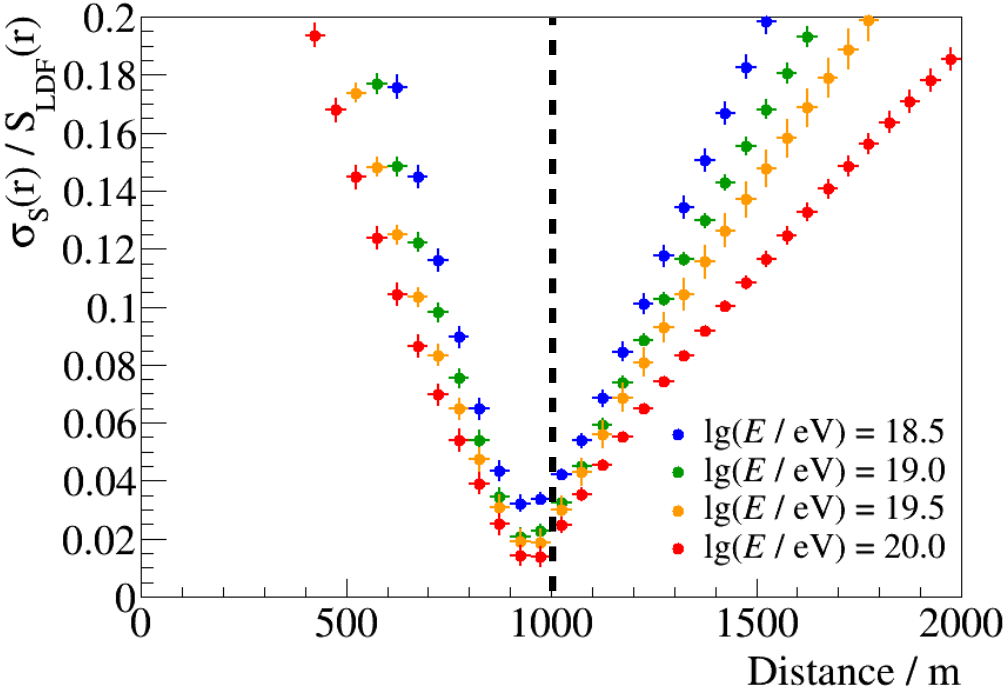


TA highest energy event from P. Sokolsky

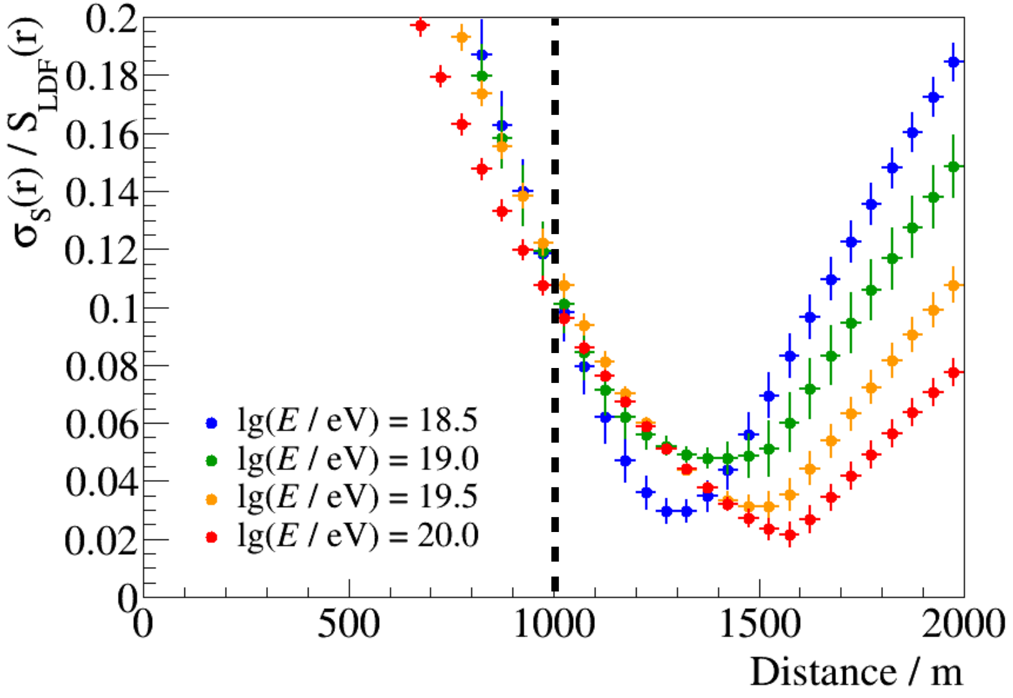
Optimal distance and saturation

WCD - Triangular grid – 1500 m
***Auger-NKG* LDF**
Proton, θ = 0°, QGSJet-II.04

Unsaturated



Saturated



- Shift of the **optimal distance** towards **larger values** (as shown in *Newton et al. (2007)*)

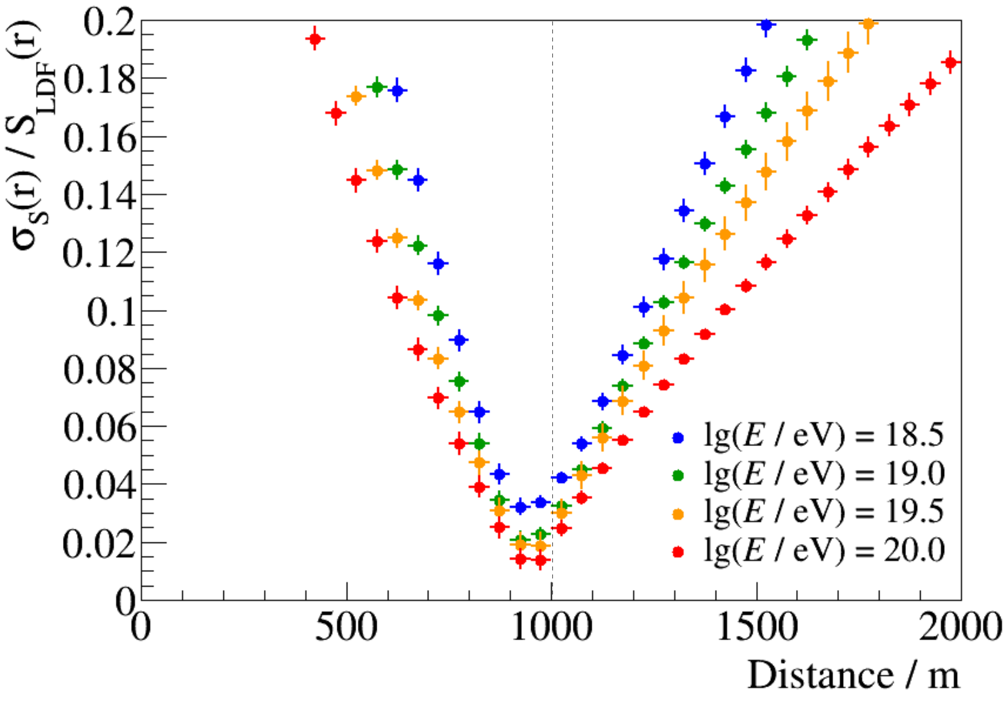
- **Dependency in energy** of the optimal distance in case of saturation (~200 m)

- Similar results on a square grid

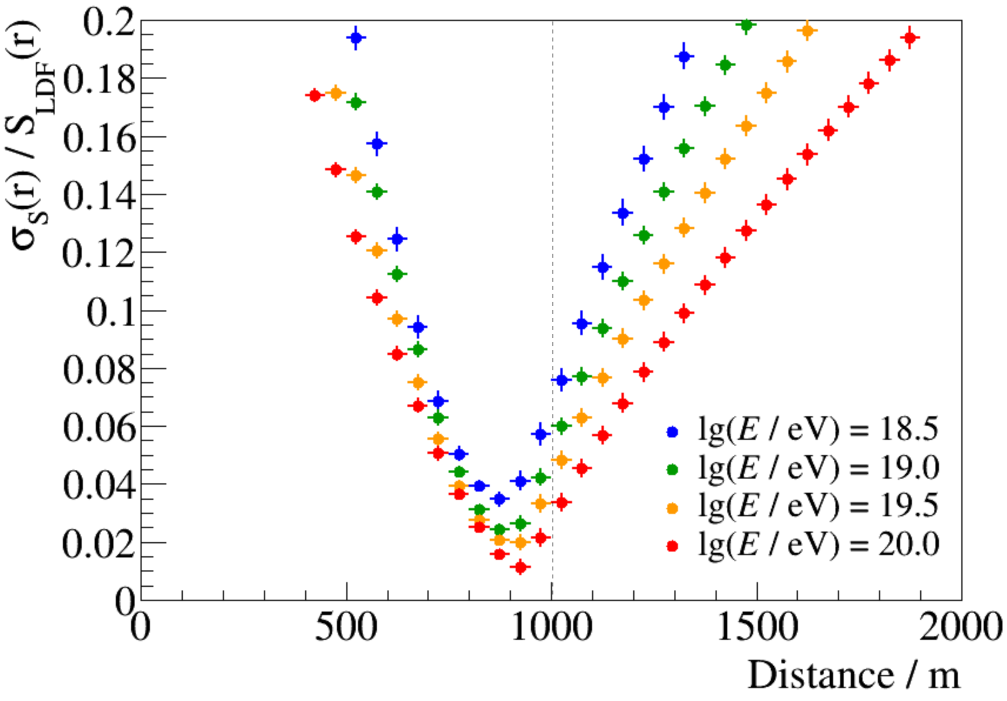
Square vs Triangular

WCD – No saturation
***Auger-NKG* LDF**
Proton, θ = 0°, QGSJet-II.04

Triangular, 1500 m



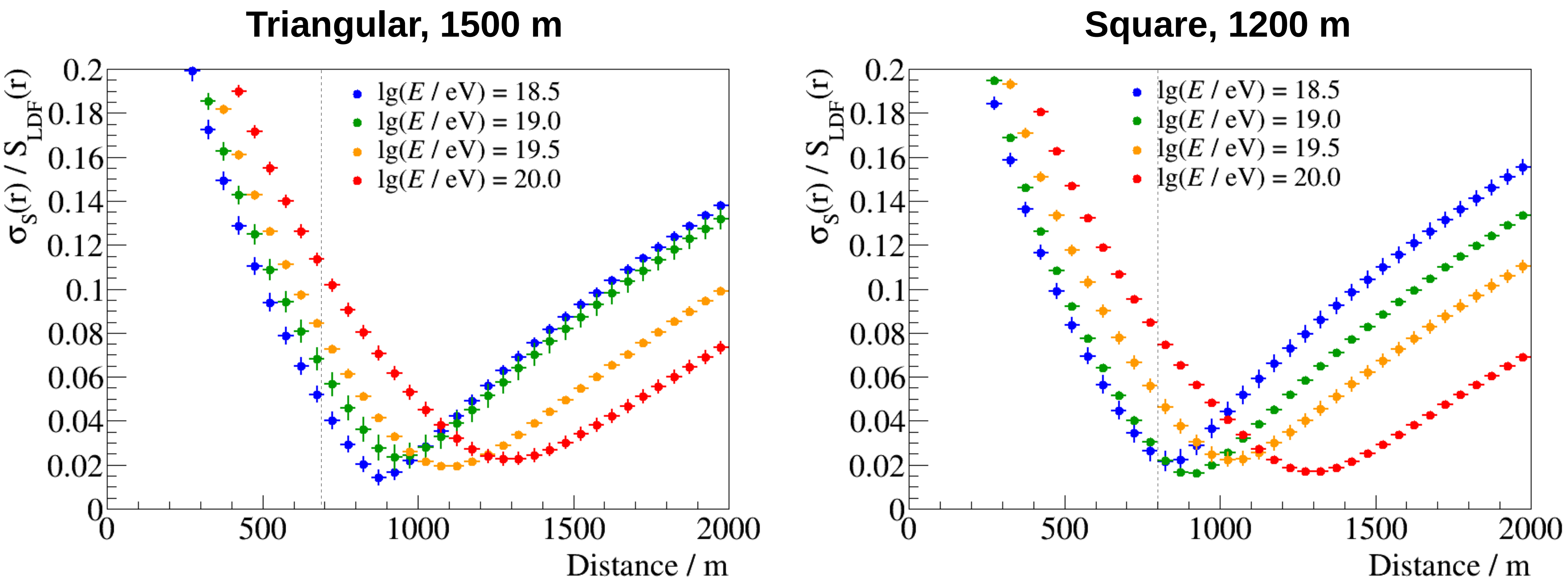
Square, 1200 m



Introduction of a **small, dependent in energy, shift of the optimal distance** (from 850 to 950 m)?

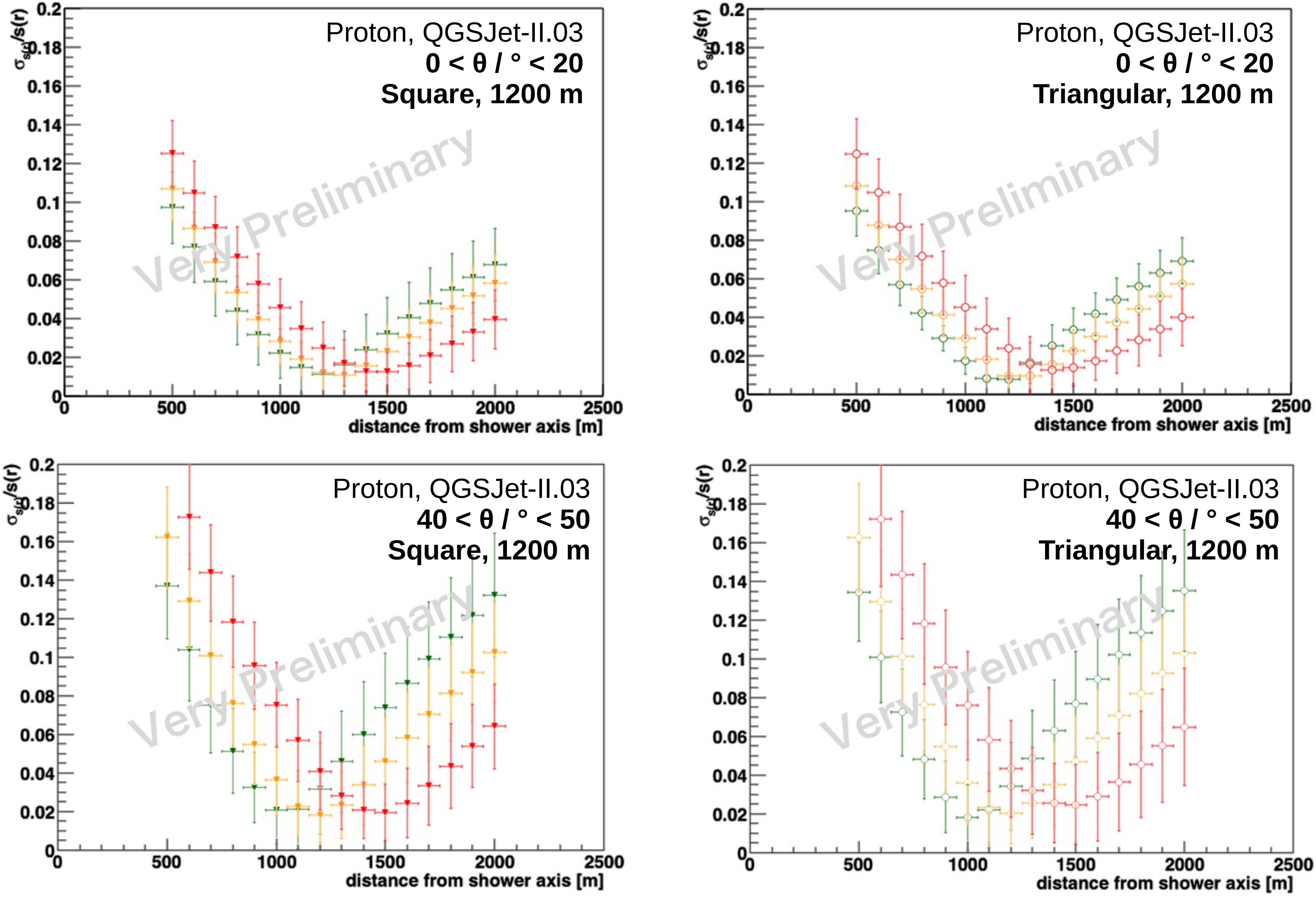
Square vs Triangular

SSD – No saturation
***AGASA* LDF**
Proton, θ = 0°, QGSJet-II.04



Different spacing and layout but **variations of the signal are the same**?

From Auger/TA working group



World tour of LDFs

Energy dependency of the optimal distance could be due to ?

- **saturation effect:** shift of the optimal distance, energy dependency amplified
- **geometry of the array:** not conclusive, small dependency in Auger-LDF only
- **parametrization of the LDF:** does it imply differences between SSD/WCD?

How to test the parametrization of the LDF? → Toy-model MC

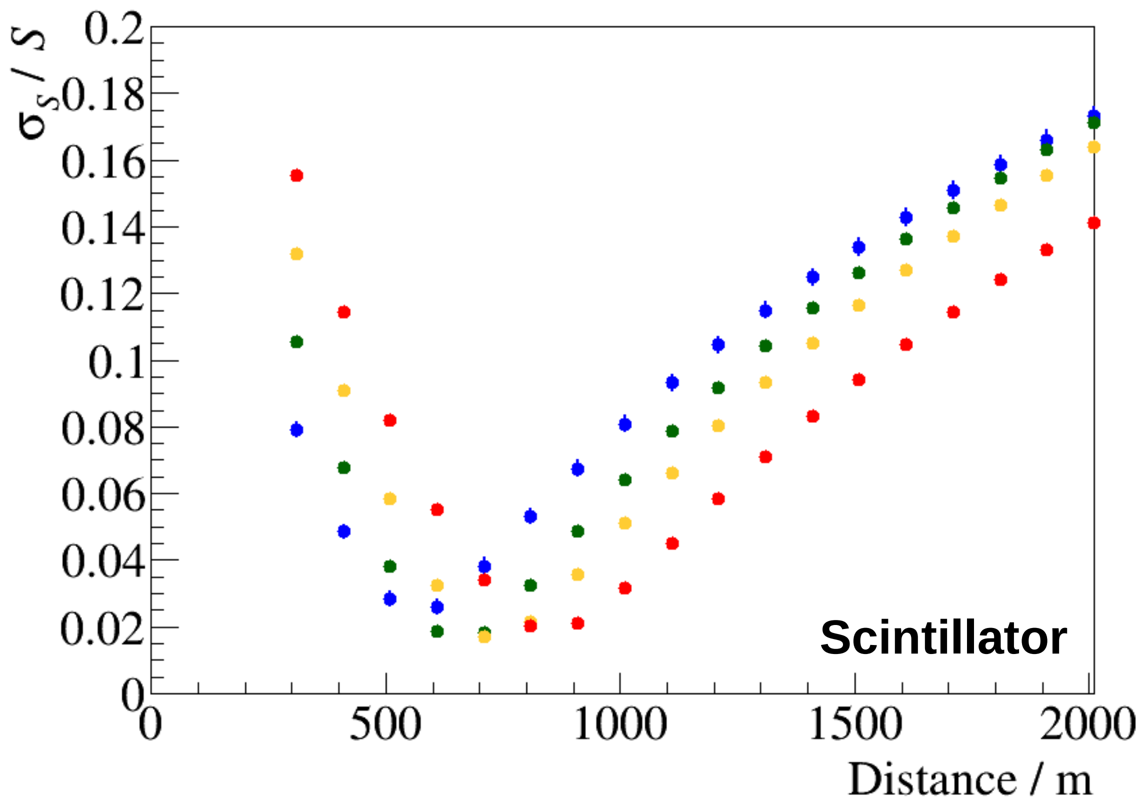
- from a particular LDF of an experiment: **creation of an event** draw on a square grid
- **reconstruction 100 times** each event following the characteristics of each experiments (likelihood, signal uncertainties, etc.)
- computation of the **optimal distance**

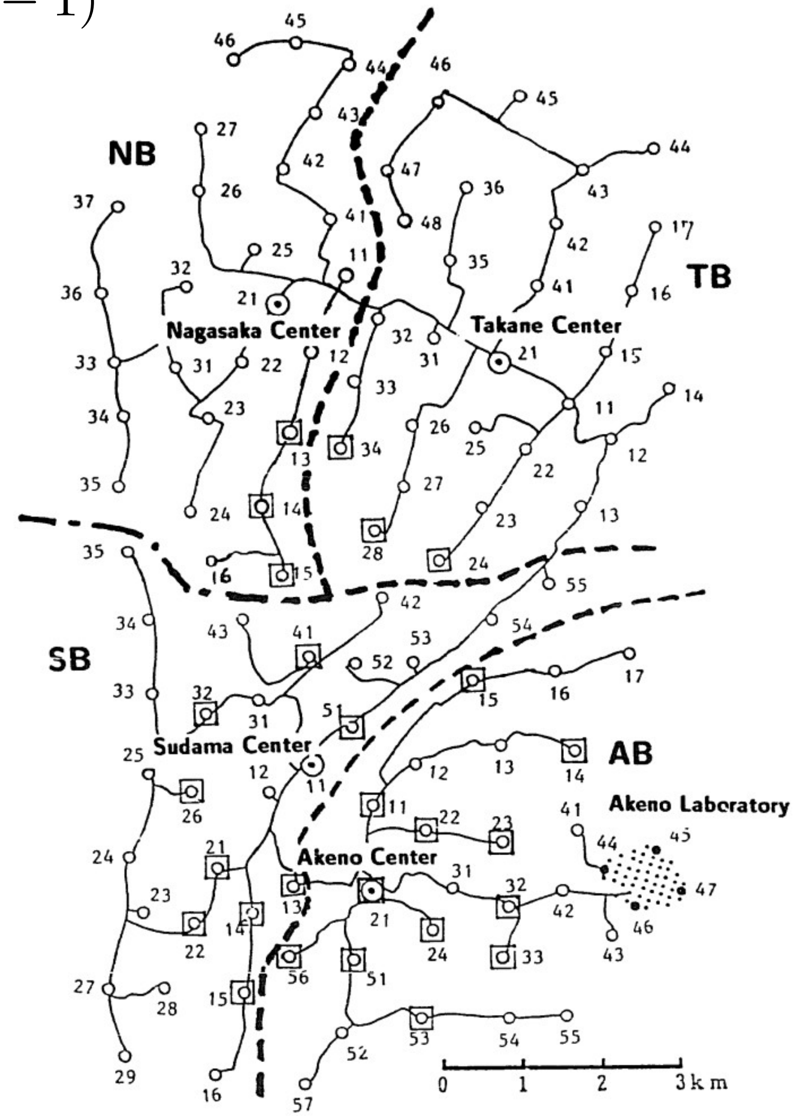
AGASA (Japan)

$$\rho(r) = A\left(\frac{r}{r_0}\right)^{-1.2}\left(1+\frac{r}{r_0}\right)^{-(\eta-1.2)}\left(1+\left(\frac{r}{1000}\right)^2\right)^{-0.6}, \quad r_0 = 91.6\,\mathrm{m}$$

$$\eta = 3.97 - 1.79(\sec\theta - 1)$$

Square grid, 1000 m, θ = 35°





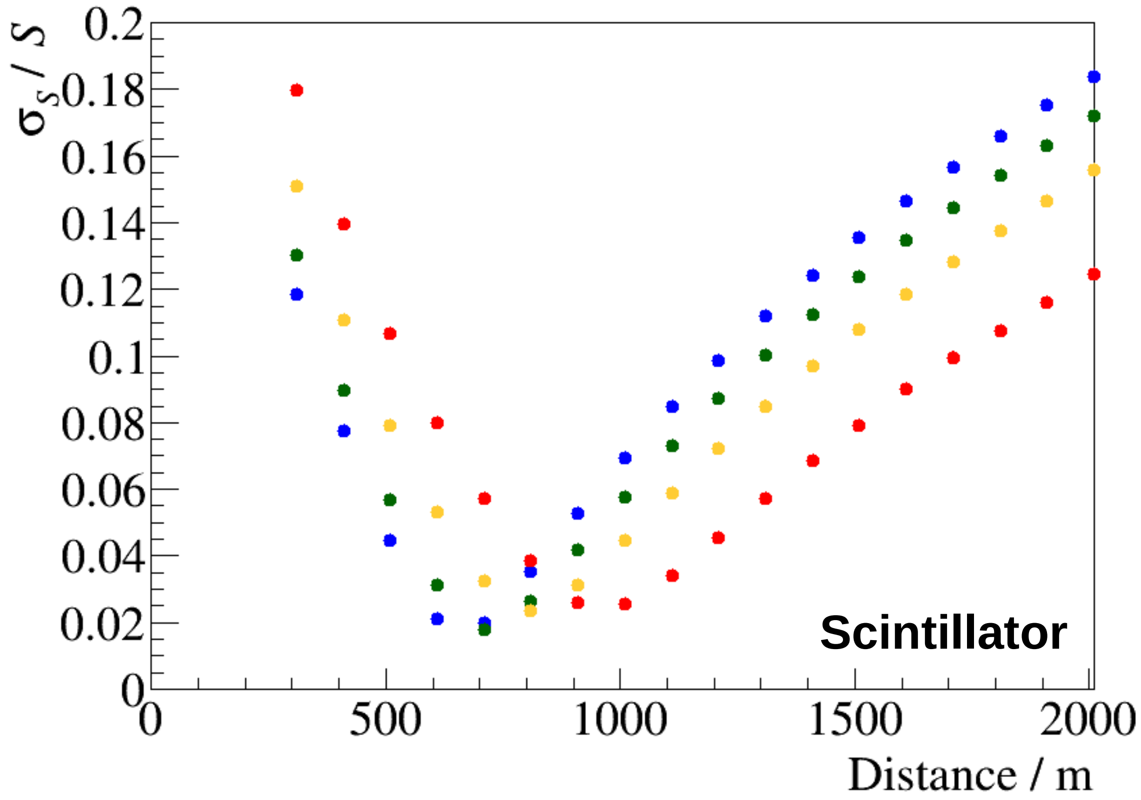
Dai et al. (1988)

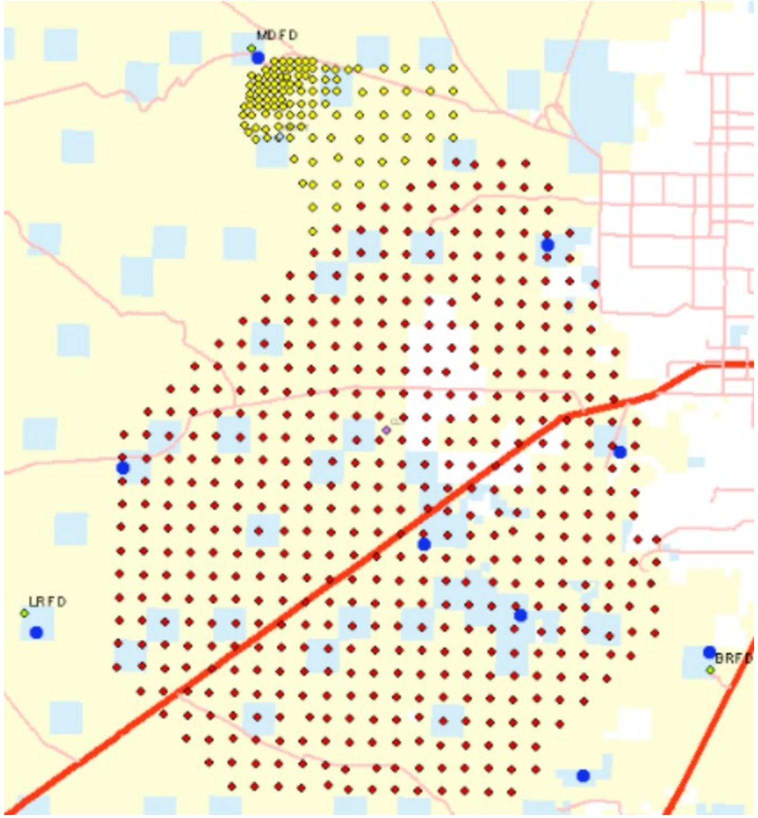
Telescope Array (Utah, USA)

$$\rho(r) = A\left(\frac{r}{r_0}\right)^{-1.2}\left(1+\frac{r}{r_0}\right)^{-(\eta-1.2)}\left(1+\left(\frac{r}{1000}\right)^2\right)^{-0.6}, \quad r_0 = 91.6\,\mathrm{m}$$

$$\eta = 3.97 - 1.79(\sec\theta - 1)$$

Square grid, 1000 m, θ = 35°





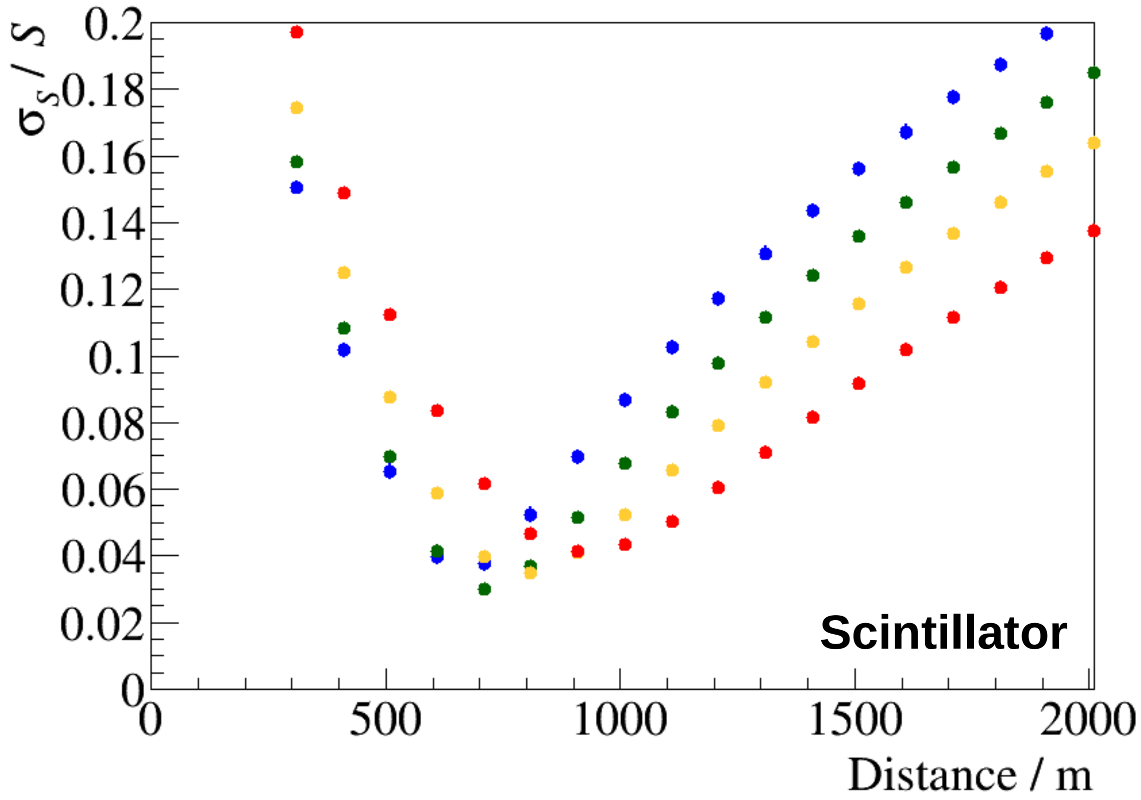
Ivanov's thesis (2012)

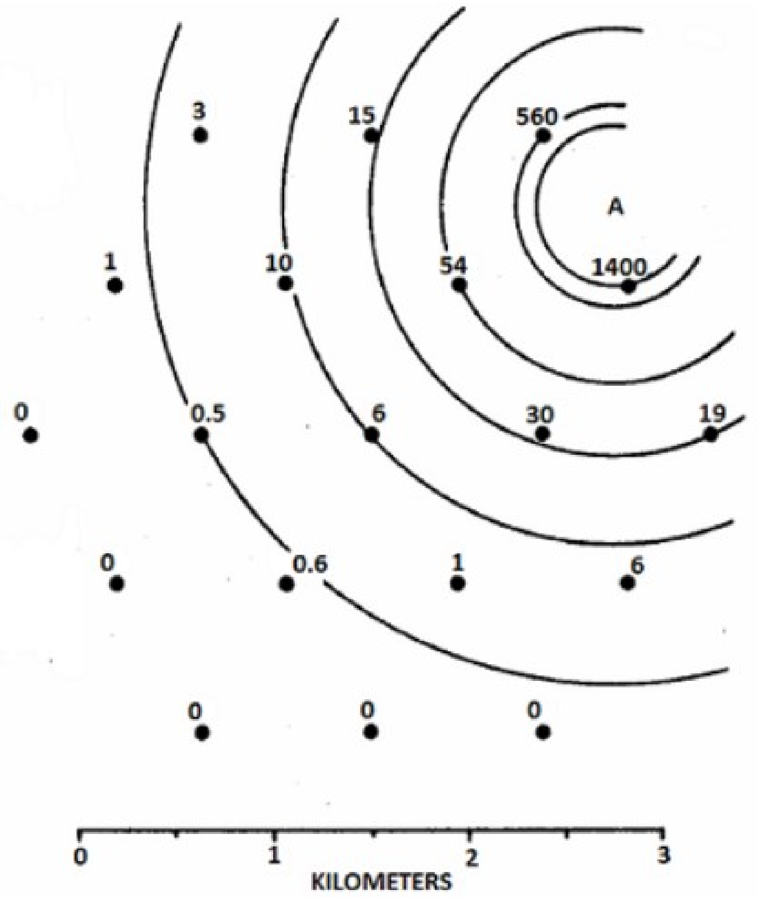
Volcano Ranch (New Mexico, USA)

$$\rho(r) = \frac{N}{r_0^2} C(\alpha, \eta) \left(\frac{r}{r_0}\right)^{-\alpha} \left(1 + \frac{r}{r_0}\right)^{-(\eta-\alpha)}, \ r_0 = f(P, T)$$

$$\eta = 3.70 - 0.57(\sec\theta - 1) + 0.085 \lg(N/10^8)$$

Square grid, 1000 m, θ = 35°





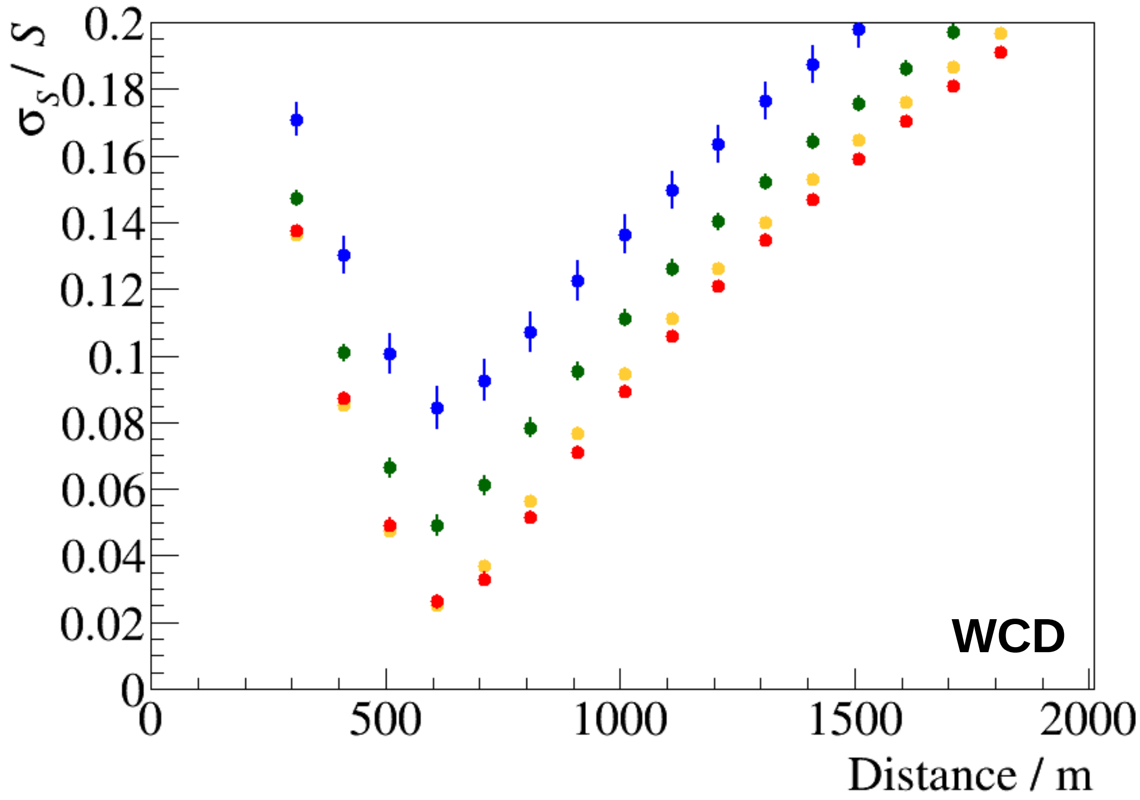
Linsley, Reid and Watson (1980)

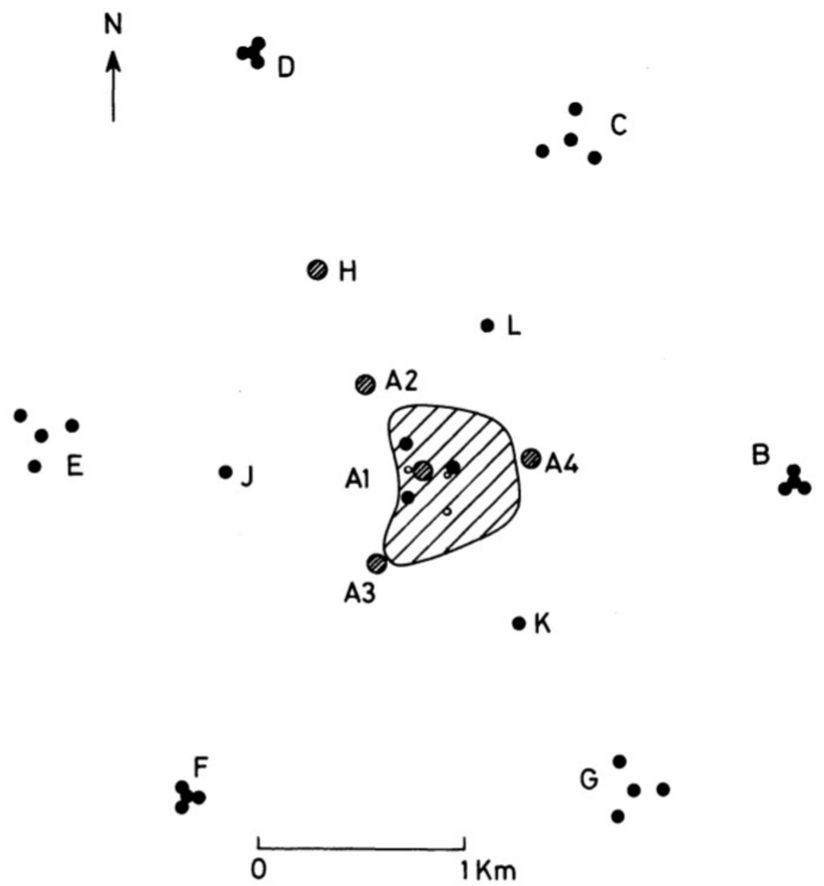
Haverah Park (Scotland)

$$\rho(r) = kr^{-(\eta + r/4000)}$$

$$\eta = 3.78 - 1.44(\sec\theta - 1)$$

Square grid, 1000 m, θ = 35°





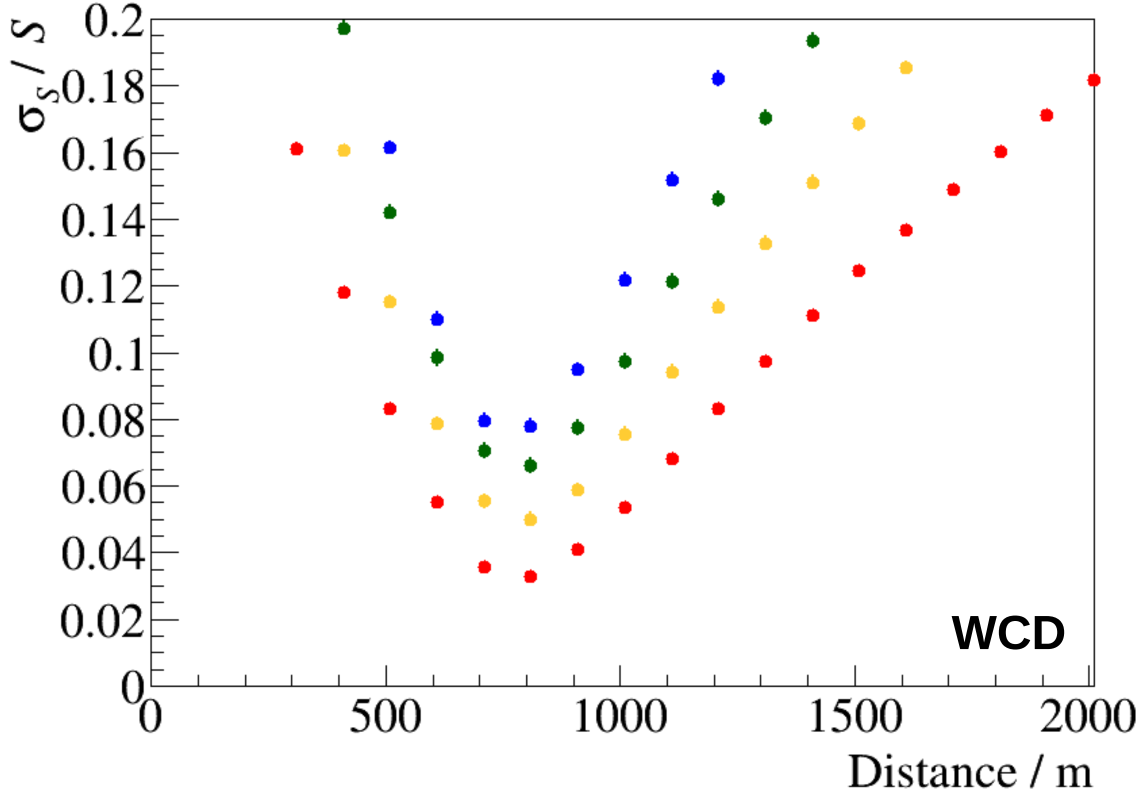
Linsley, Reid and Watson (1980)

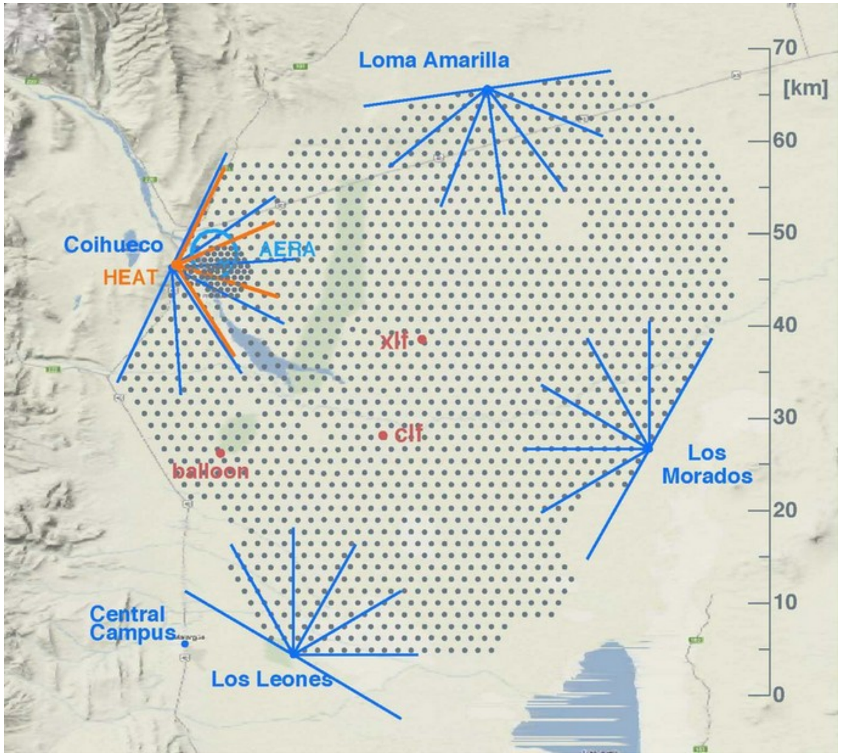
Auger-WCD (Argentina)

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+r_0}{1000+r_0}\right)^{-\gamma}\ ,\ r_0 = 700\,\mathrm{m}$$

$$\eta = f(\theta, S(1000))$$

Square grid, 1000 m, θ = 35°





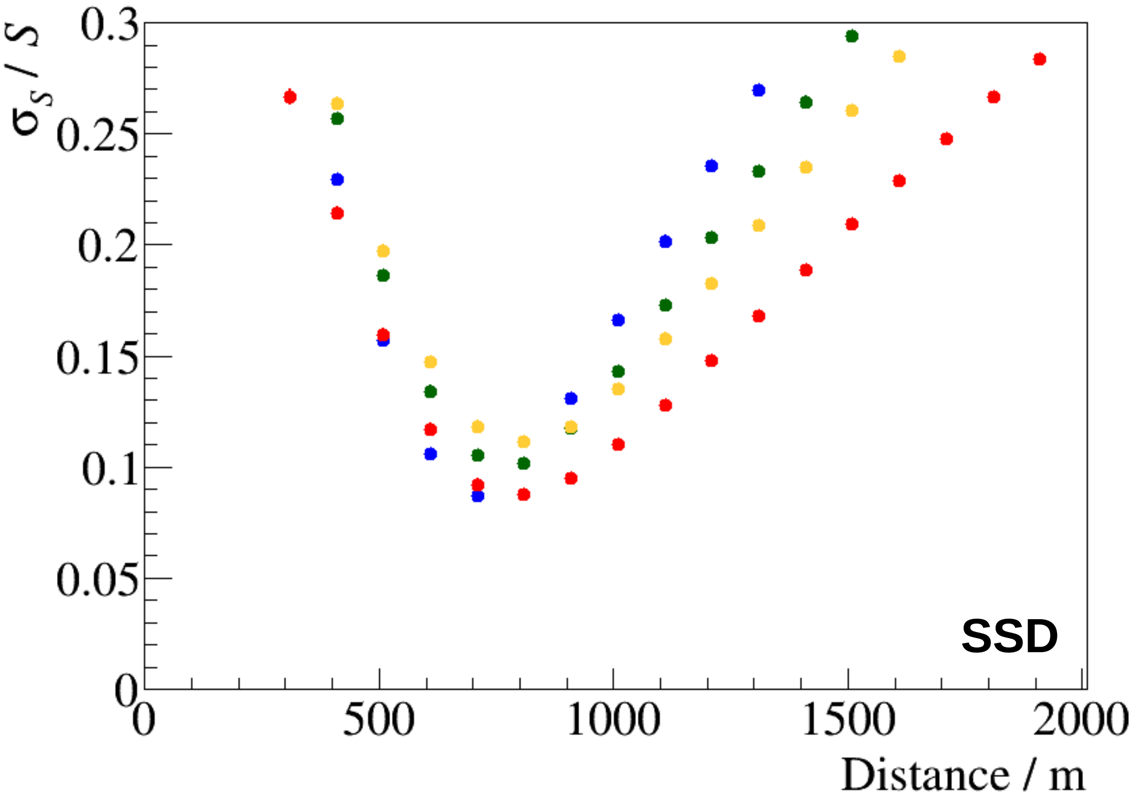
A. Taboada's thesis (2019)

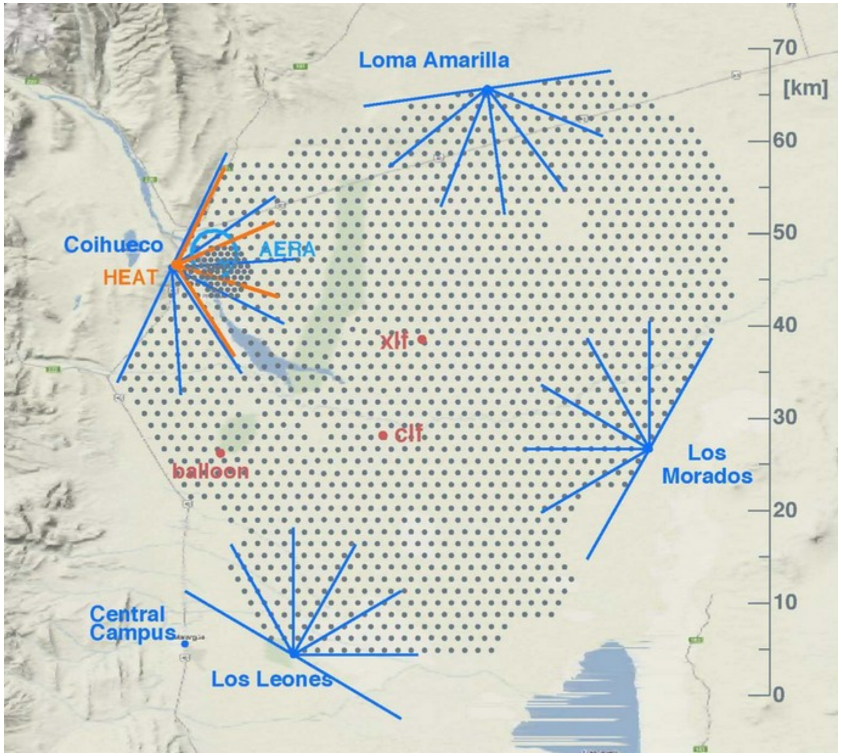
Auger-SSD (Argentina)

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+r_0}{1000+r_0}\right)^{-\gamma}\ ,\ r_0 = 700\,\mathrm{m}$$

$$\eta = f(\theta, S(1000))$$

Square grid, 1000 m, θ = 35°



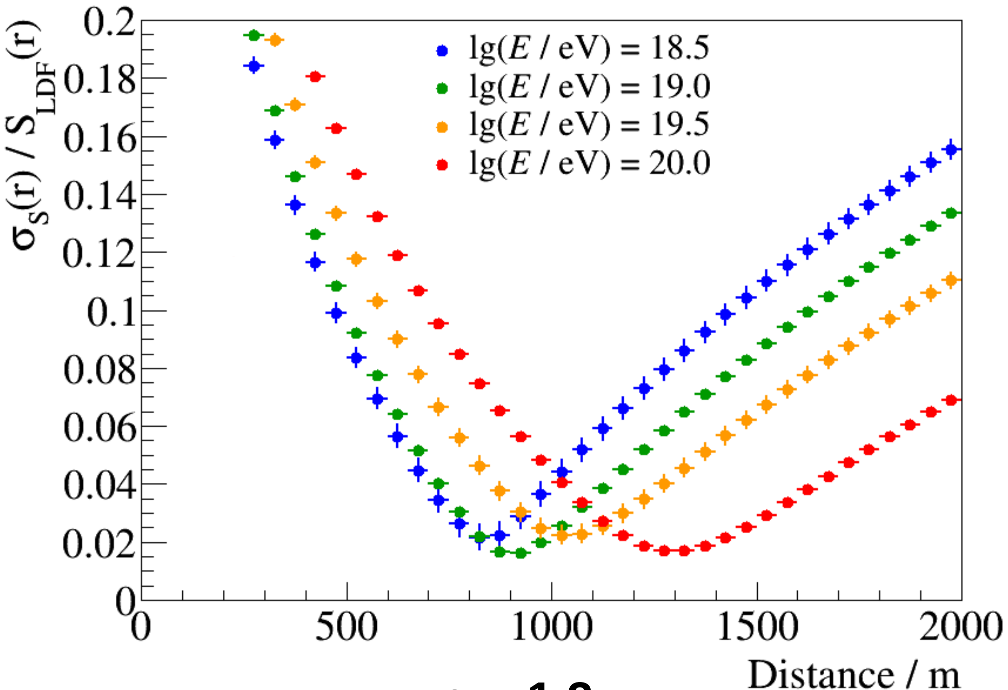


A. Taboada's thesis (2019)

Change of LDF parameters

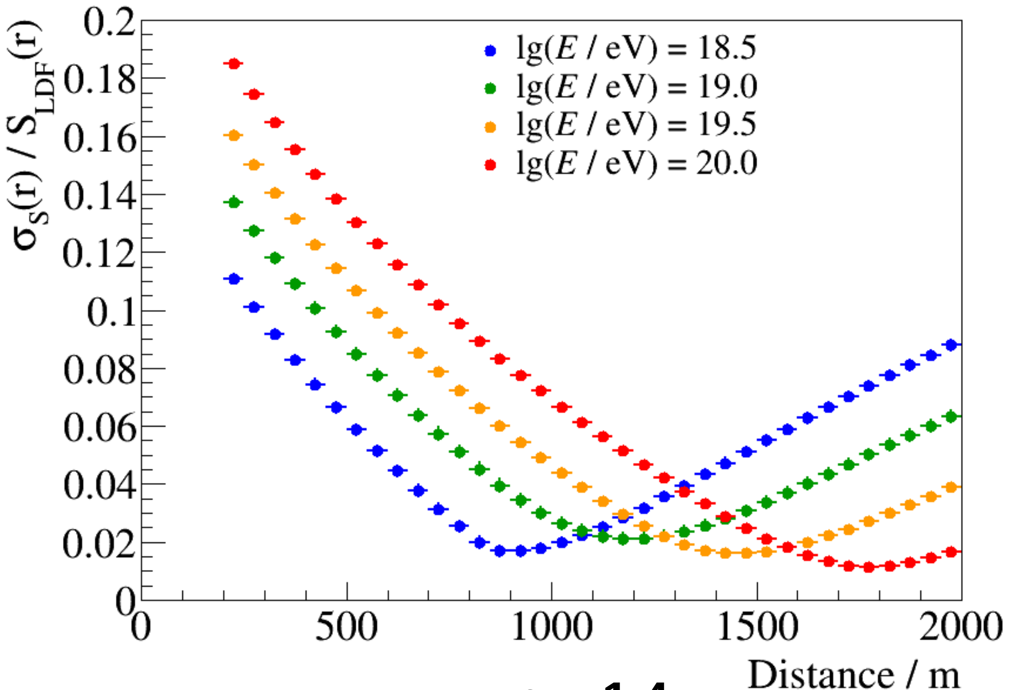
SSD, **no saturation**
Square, 1200 m
Proton, lg(E/eV) = 19, θ = 48°, QGSJet-II.04

***Standard AGASA* LDF**



α = 1.2
η = 3.2
r_0 = 100 m

***Modified AGASA* LDF**

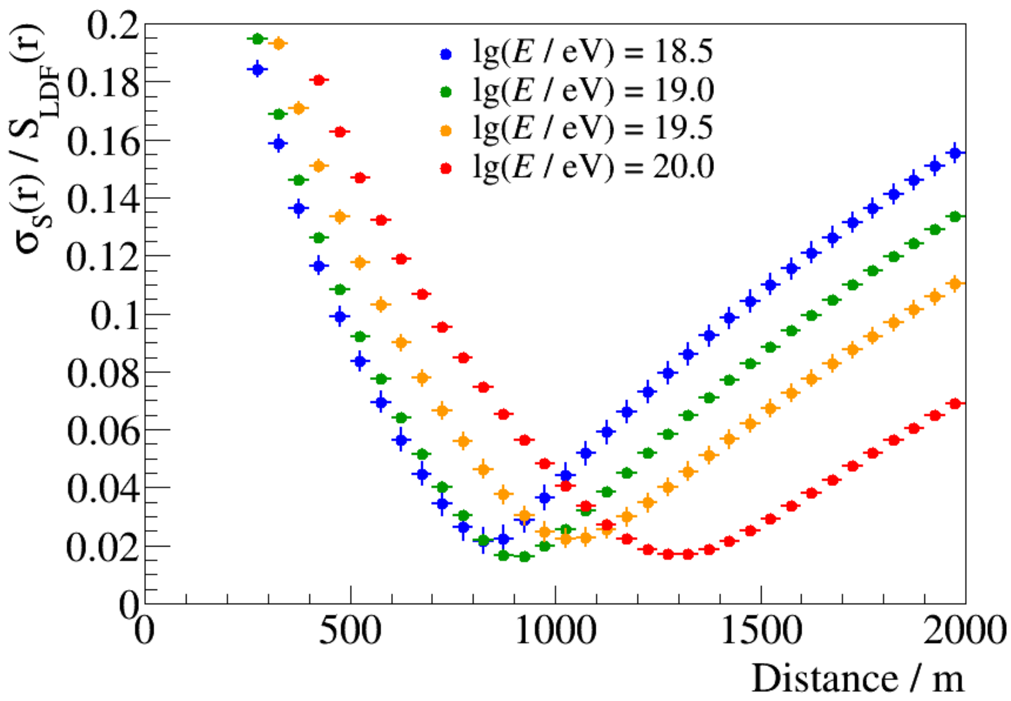


α = 1.4
η = 5.7
r_0 = 700 m

Huge change of the optimal distance

Is there a set of values of (r_0, α, η) for which the optimal distance is **independent of energy**?
In each energy and zenith bins, using a χ^2, check all sets of (r_0, α, η)

Interlude



<u>Energy dependency of the optimal distance could be due to</u> ?

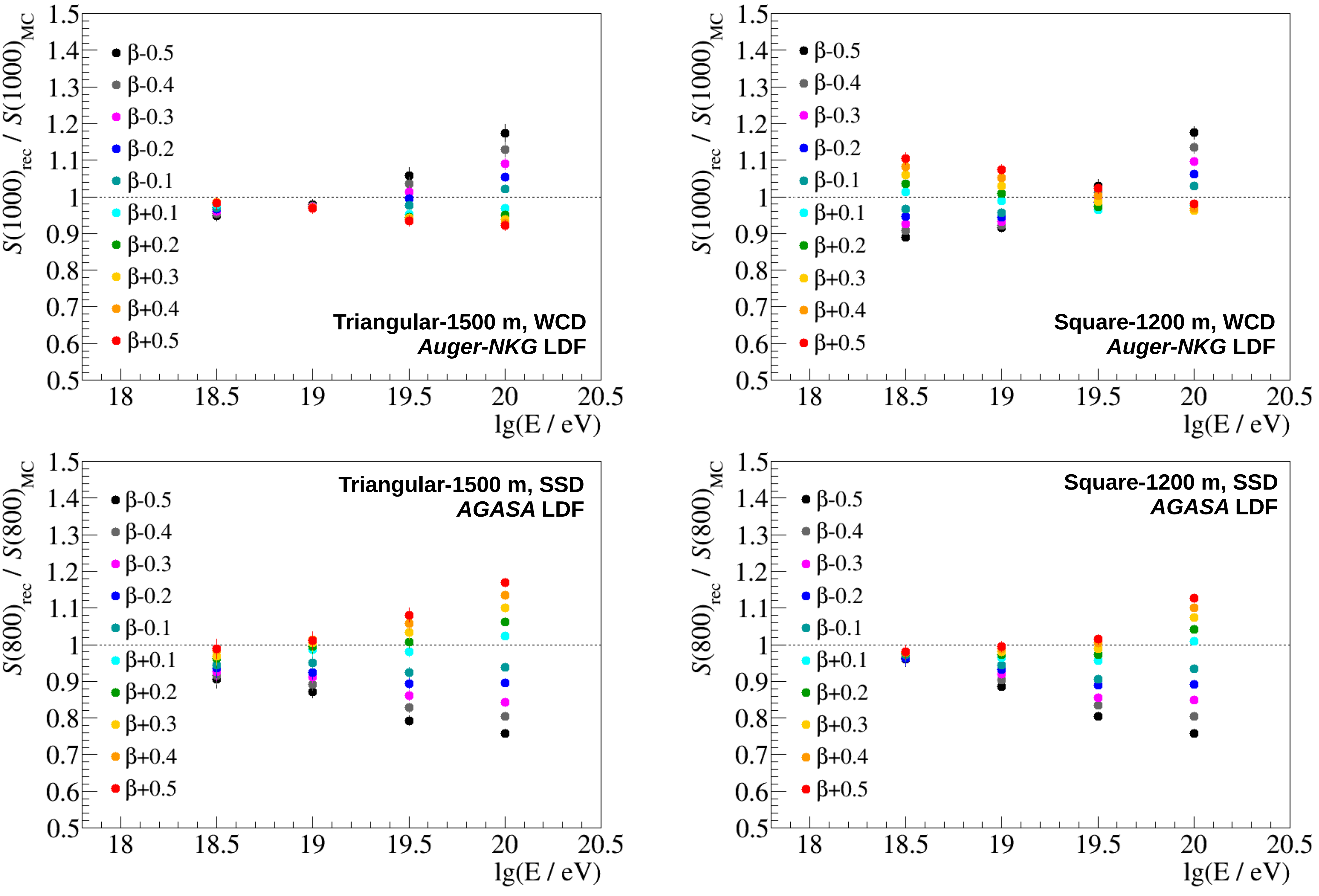
- saturation effect → saturation is responsible of a shift of the optimal distance towards the closest distance at which a station has a non-saturated signal

- square vs triangular grid → first check from TA seem to invalidate this hypothesis
→ spacing and effect from the saturation ?

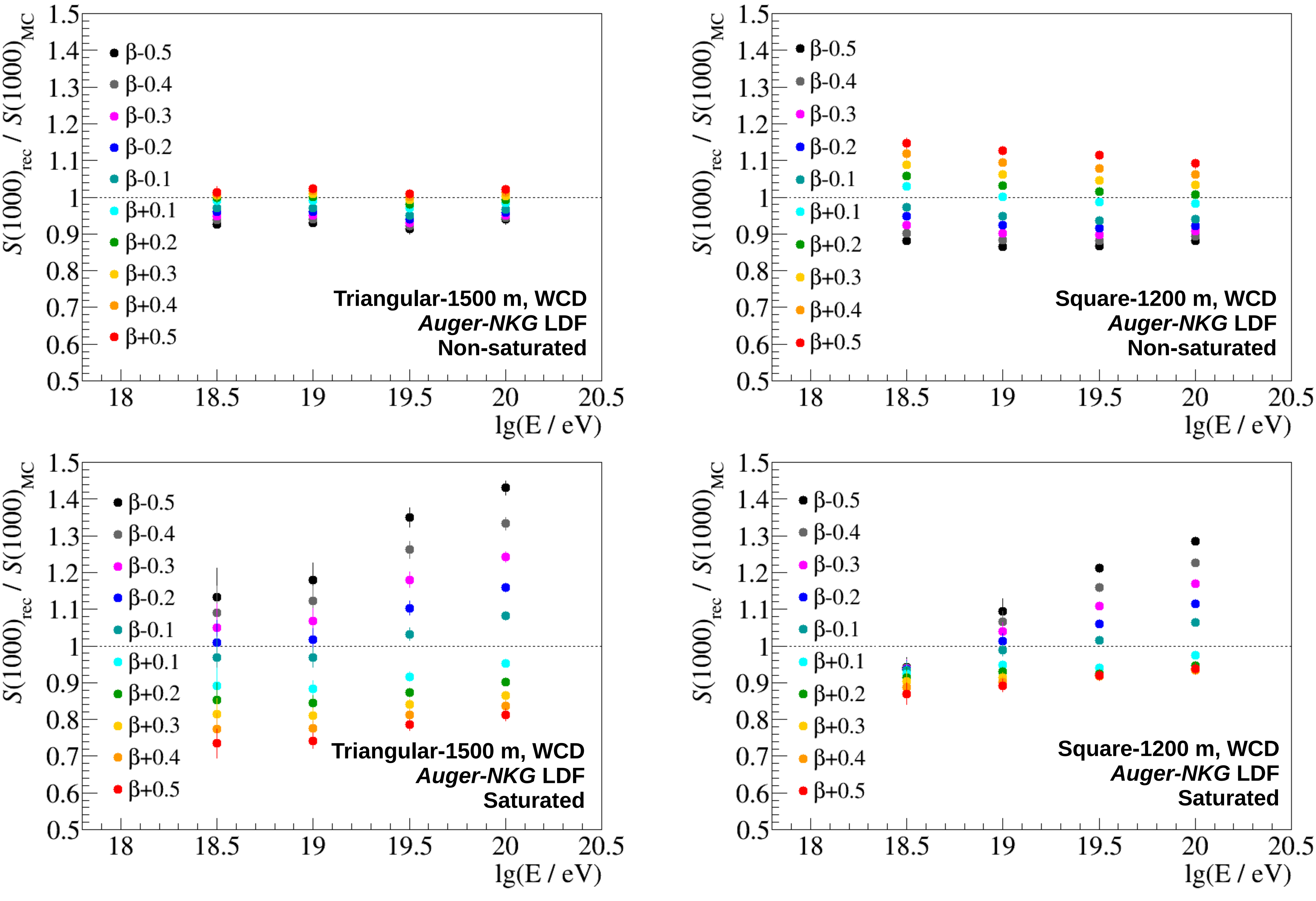
- **AGASA-LDF itself (*Dai et al. 1988*): Is it possible to find a parametrization removing the dependency in energy?**

Chapter 2:
Impact on the energy spectrum?

Fluctuations of *S*(1000) for vertical events

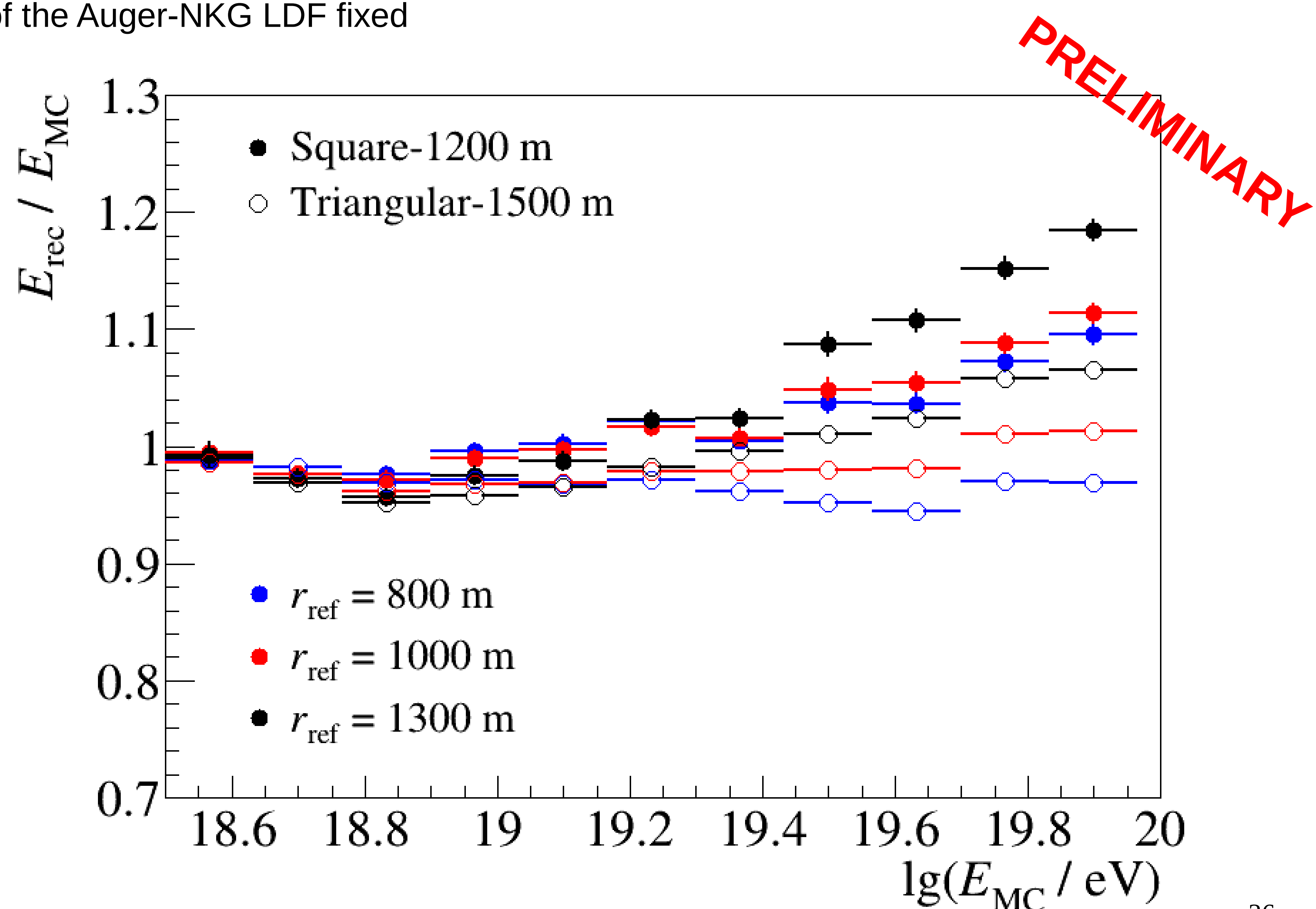


What about saturation?



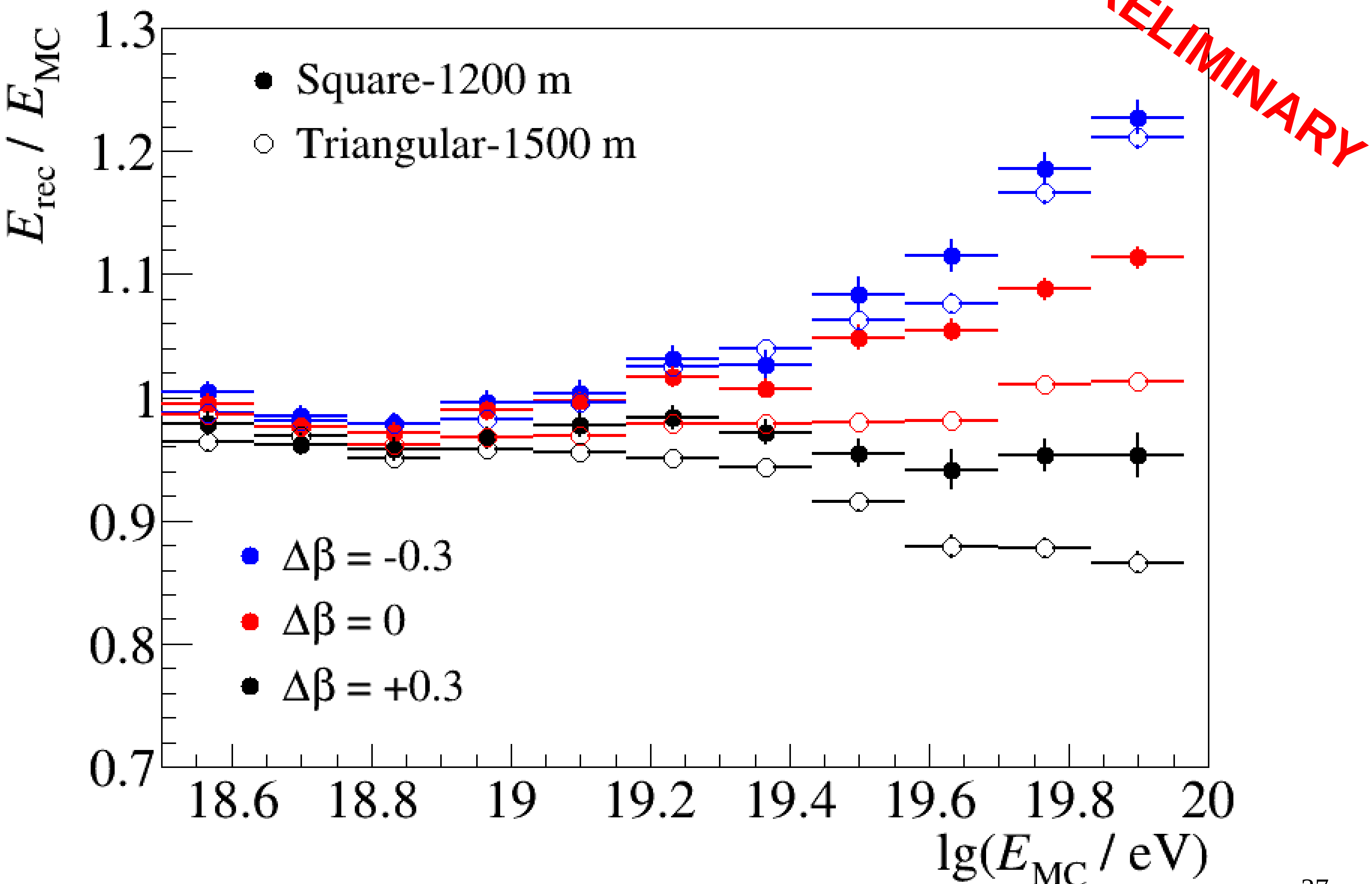
What about the energy?

Slope of the Auger-NKG LDF fixed



What about the energy?

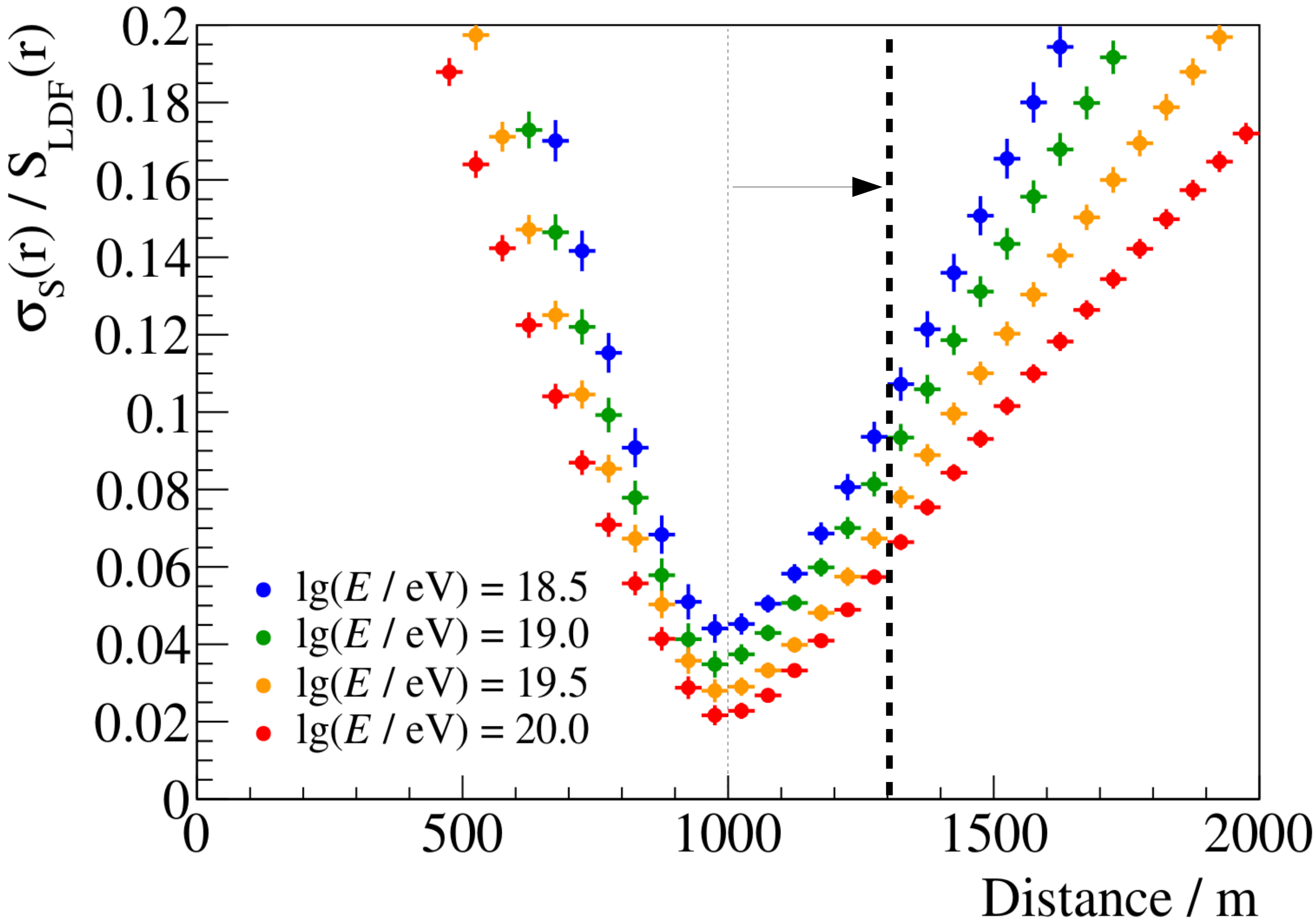
Optimal distance fixed **at 1000 m**



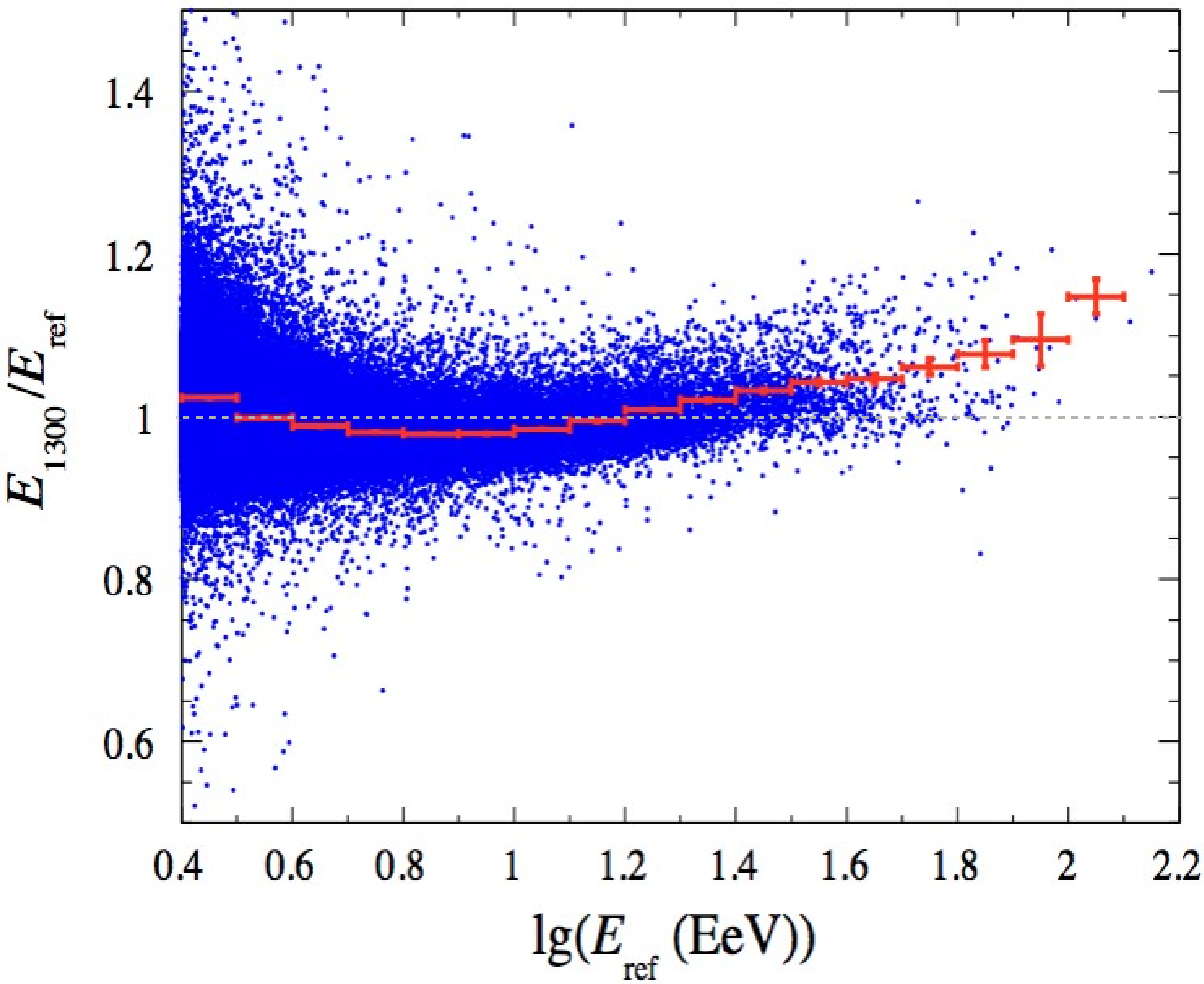
Use of *non-optimal* distance

QGSJet-II.04
Proton
$\theta = 0^{\circ}$

WCD - Triangular grid – 1500 m
***Auger-NKG* LDF**



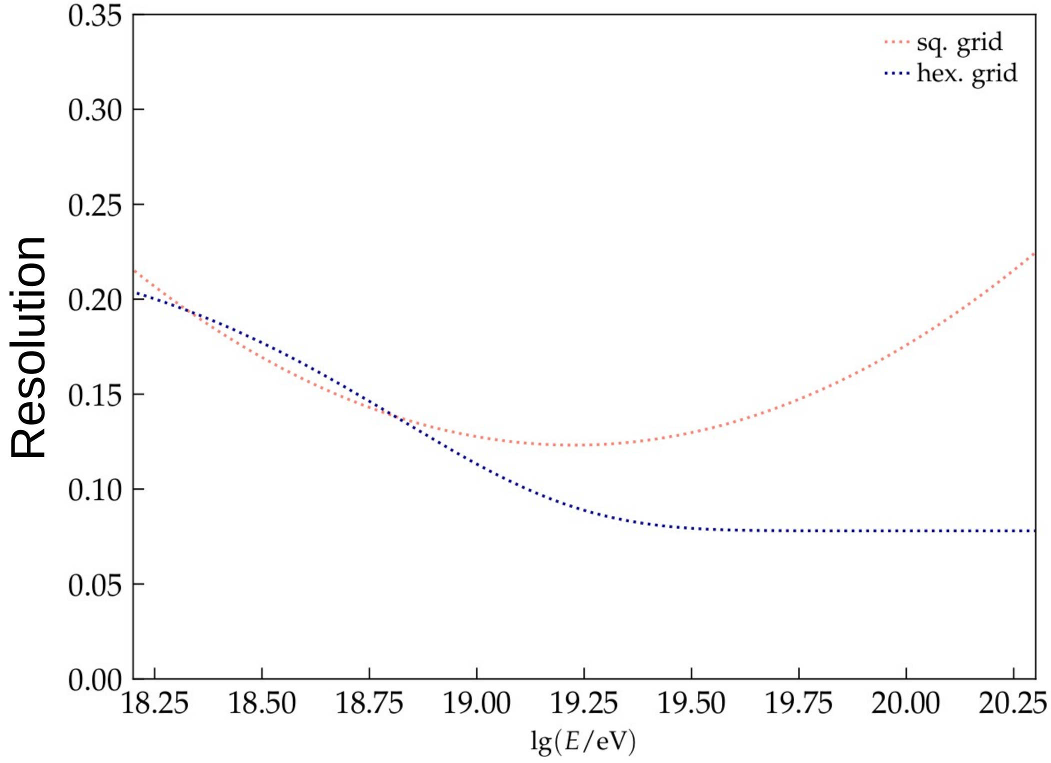
Source of non-linearities in real-data?

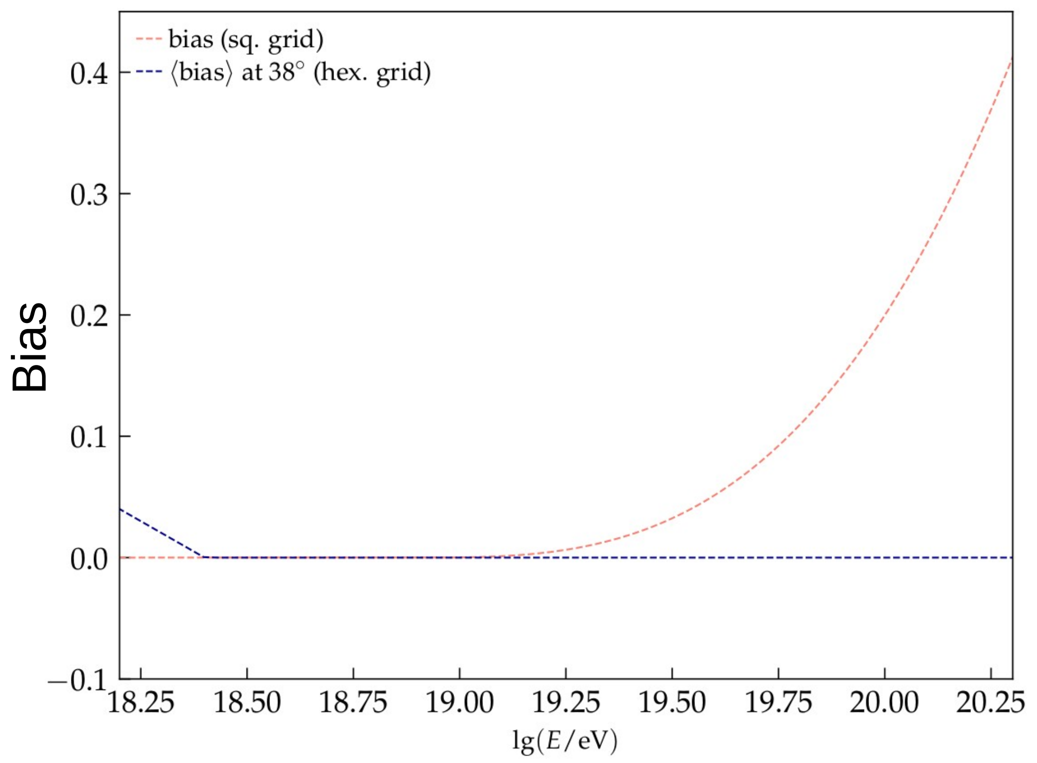


Non-linearities : increase to 15% bias from 10 EeV to 100 EeV

Bias and resolution

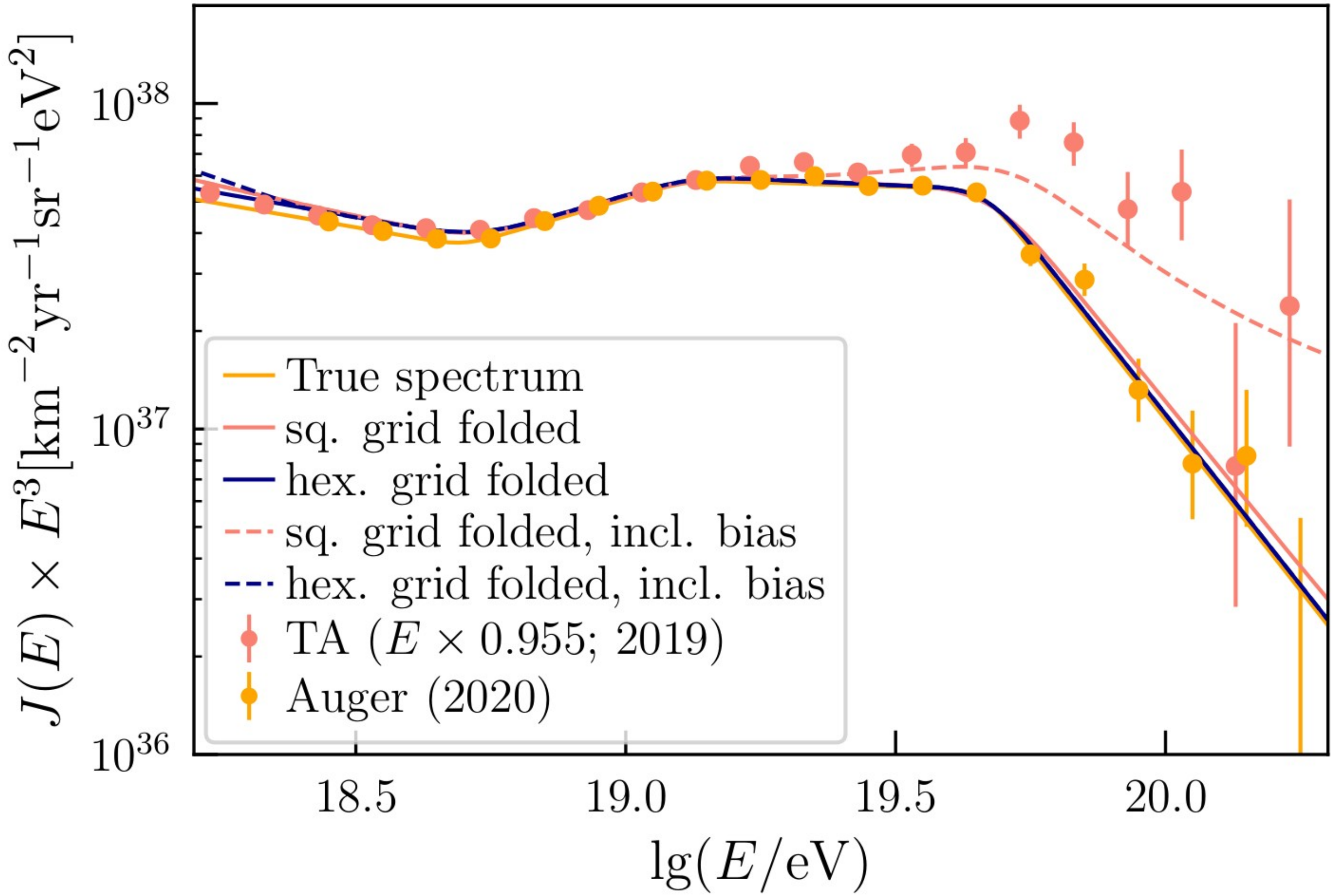
hex. grid: standard Auger array – bias and resolution from *Phys. Rev. D 102, 062005 (2020)*
sq. grid: SSD on a 1200 m squared array





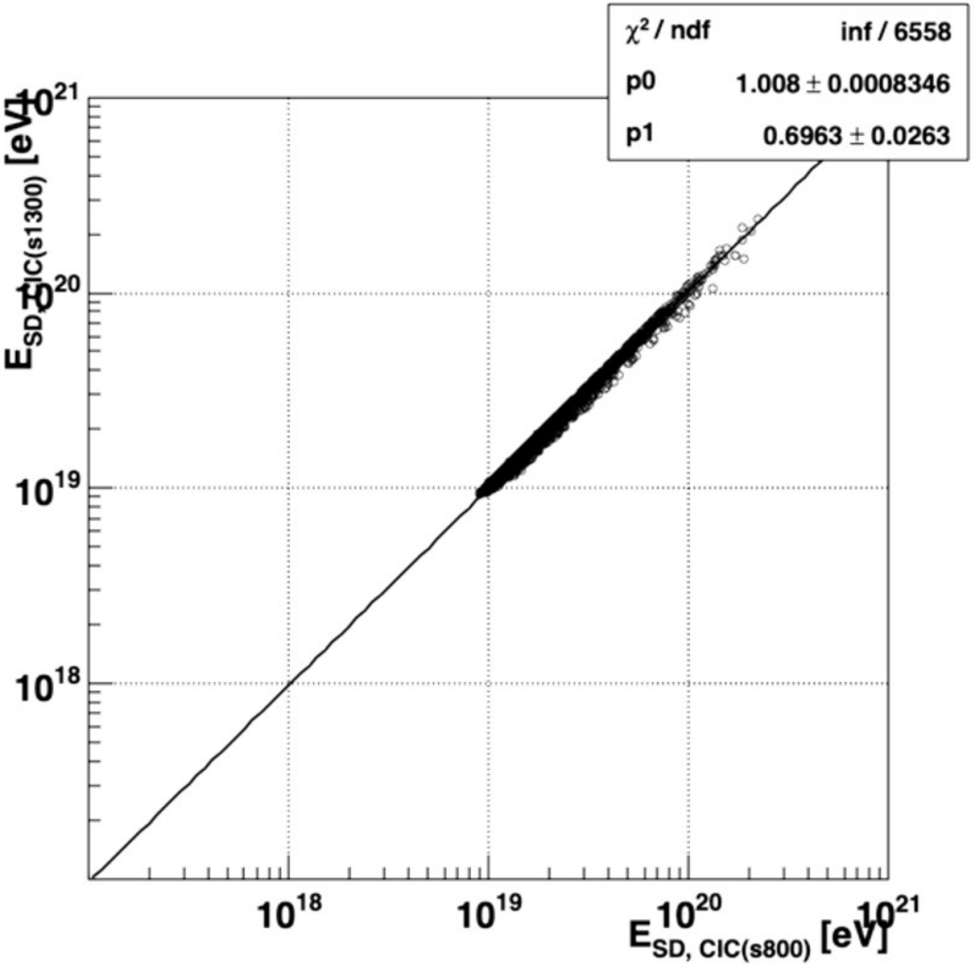
Impact on the spectrum

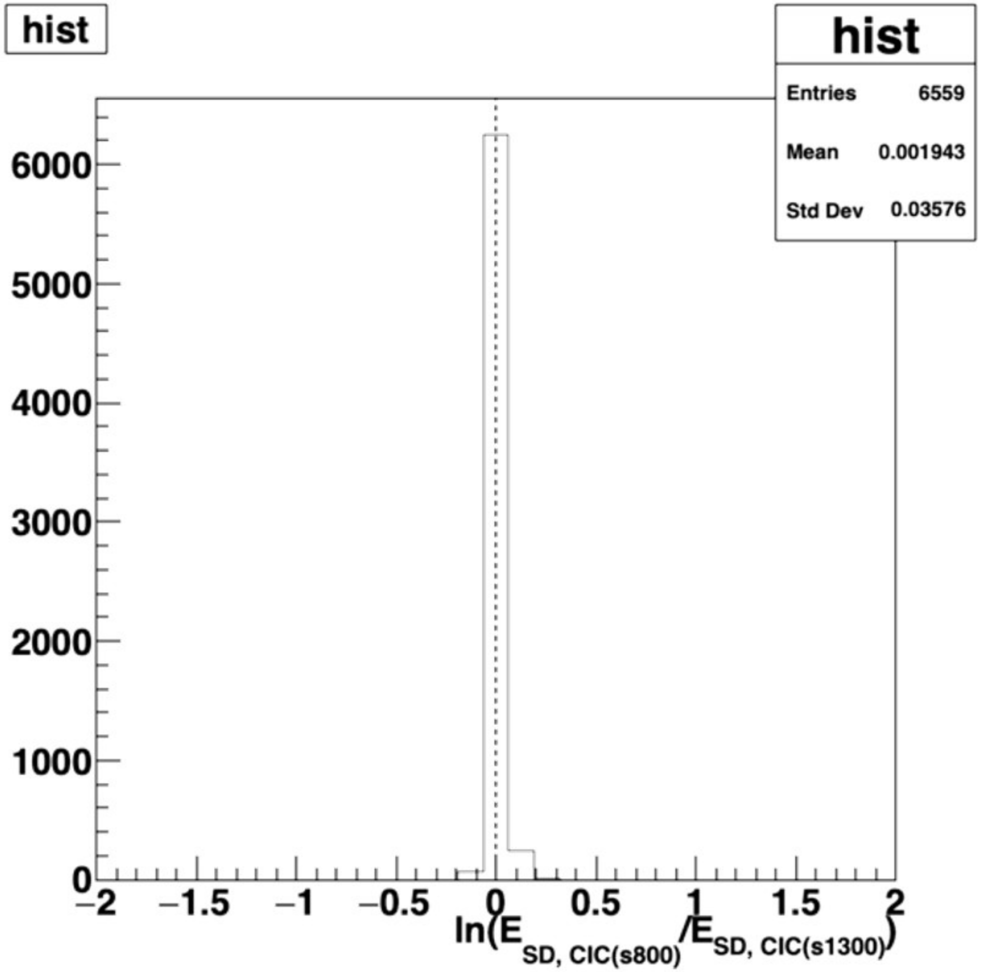
hex. grid: standard Auger array – bias and resolution from *Phys. Rev. D 102, 062005 (2020)*
sq. grid: SSD on a 1200 m squared array



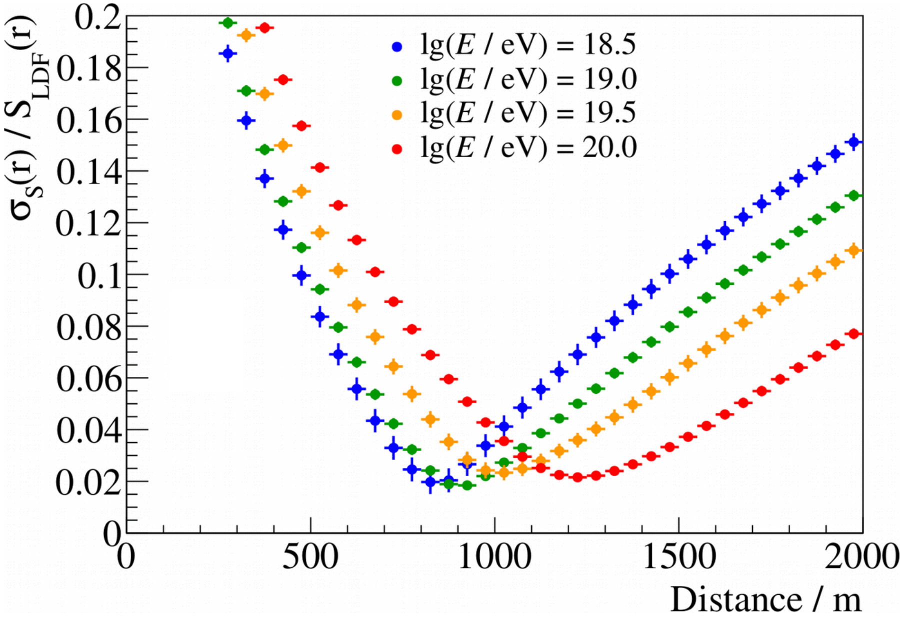
UHECR2022…

Presentation from **Valerio Verzi**, for the Auger and TA collaborations





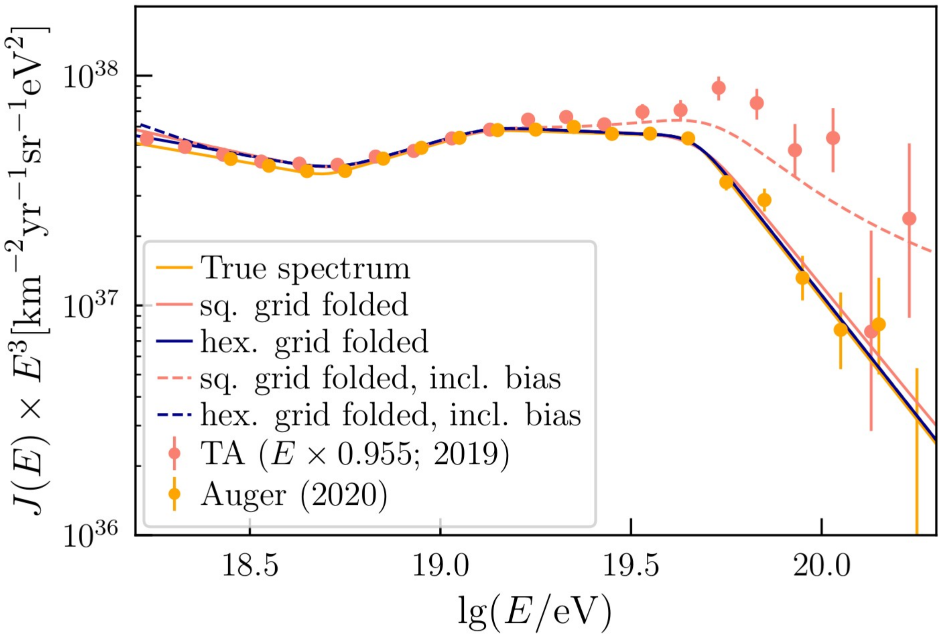
End of the story?



Origin of the energy-dependent optimal distance **is complex** :
→ to which extent the parametrization of the **shape of the LDF** is determined by the detectors?

3 contributors:

- unknown shape of the true LDF
- saturation of the detectors
- geometry of the array



Lack of knowledge of the true LDF impacts the reconstructed spectrum
In Auger, systematics derived by projecting uncertainties on the slope into the energy

Combining a non-optimal distance with variation of the slope on a different grid?

Only?

Optimal reference distance and its implication on the ~~(Auger)~~ Cosmic Rays Energy Spectrum

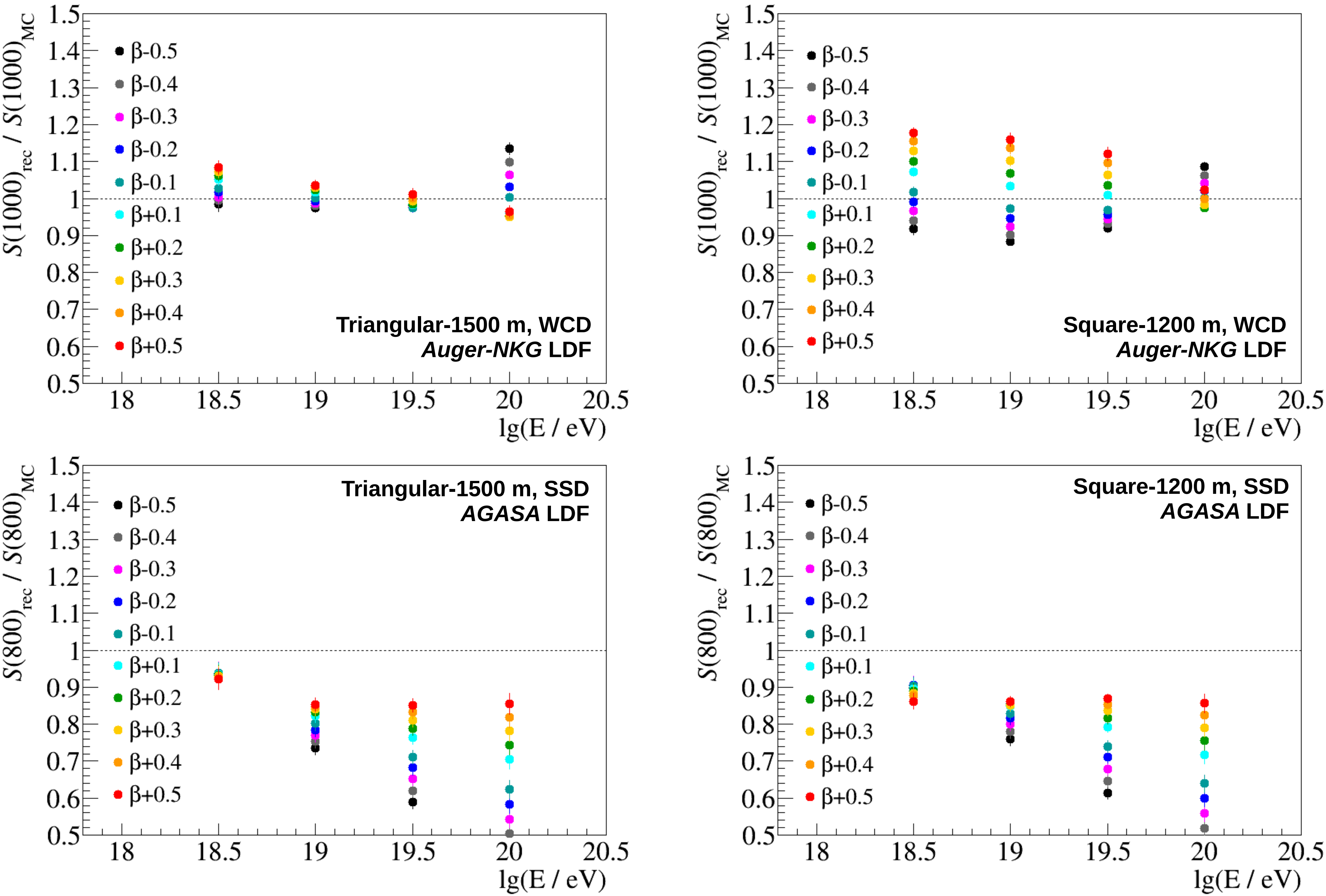
O. Deligny, I. Lhenry-Yvon, Q. Luce, M. Roth, D. Schmidt, A.A. Watson

Trugarez !*

* Thank you!

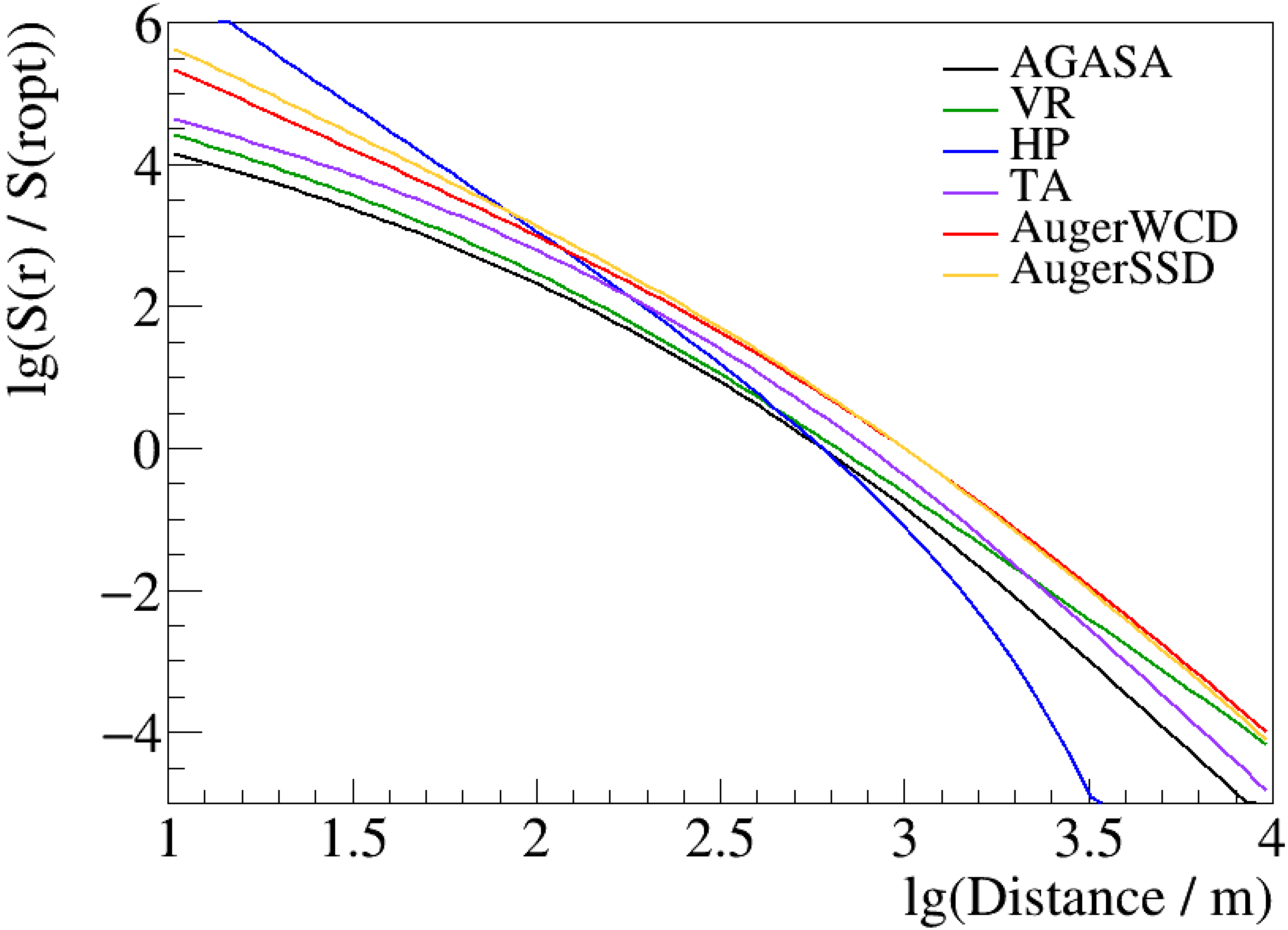
Back-up

Fluctuations of *S*(1000) - θ=48°



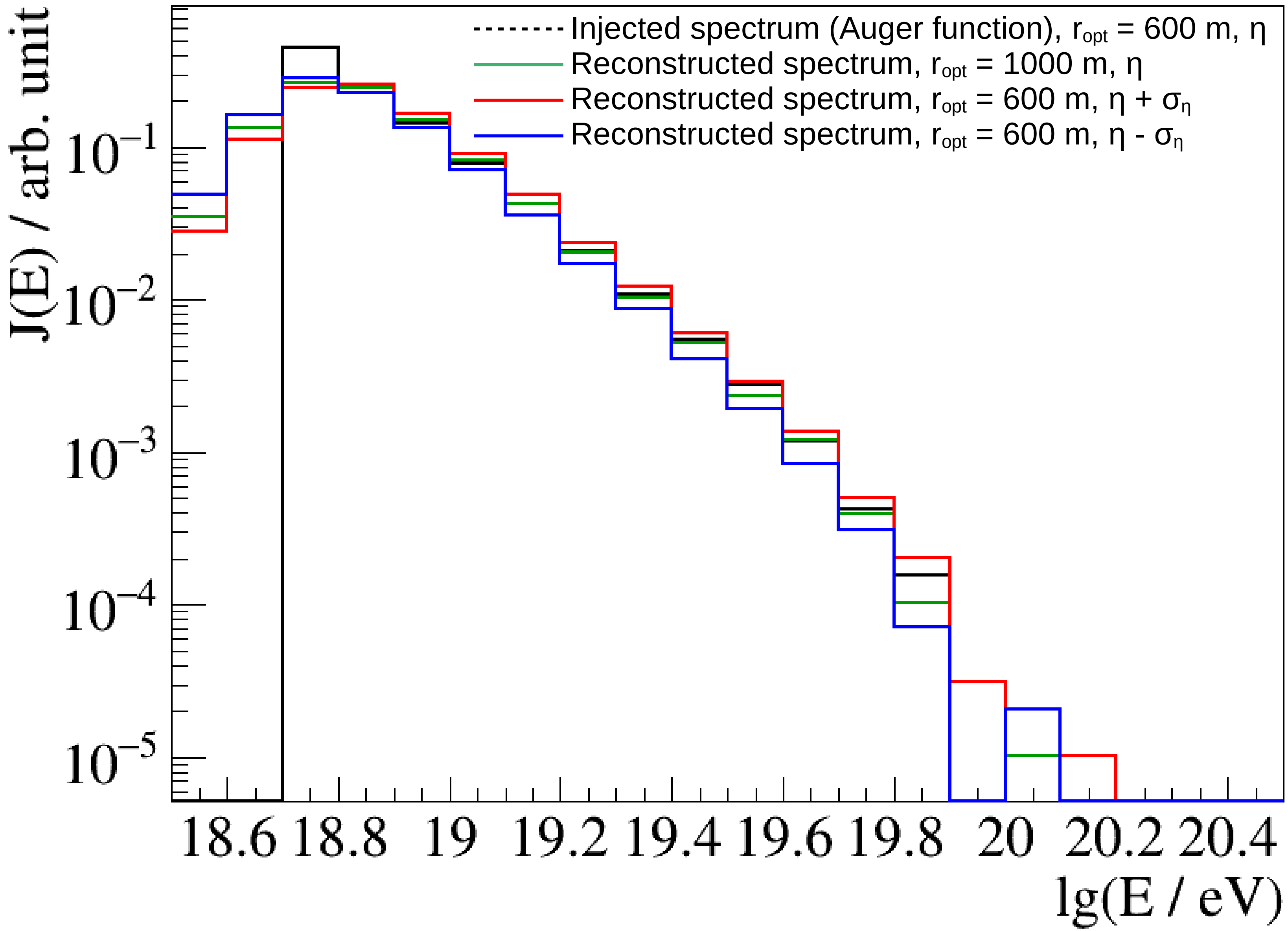
LDFs

lg(E/eV) = 19, θ = 35°



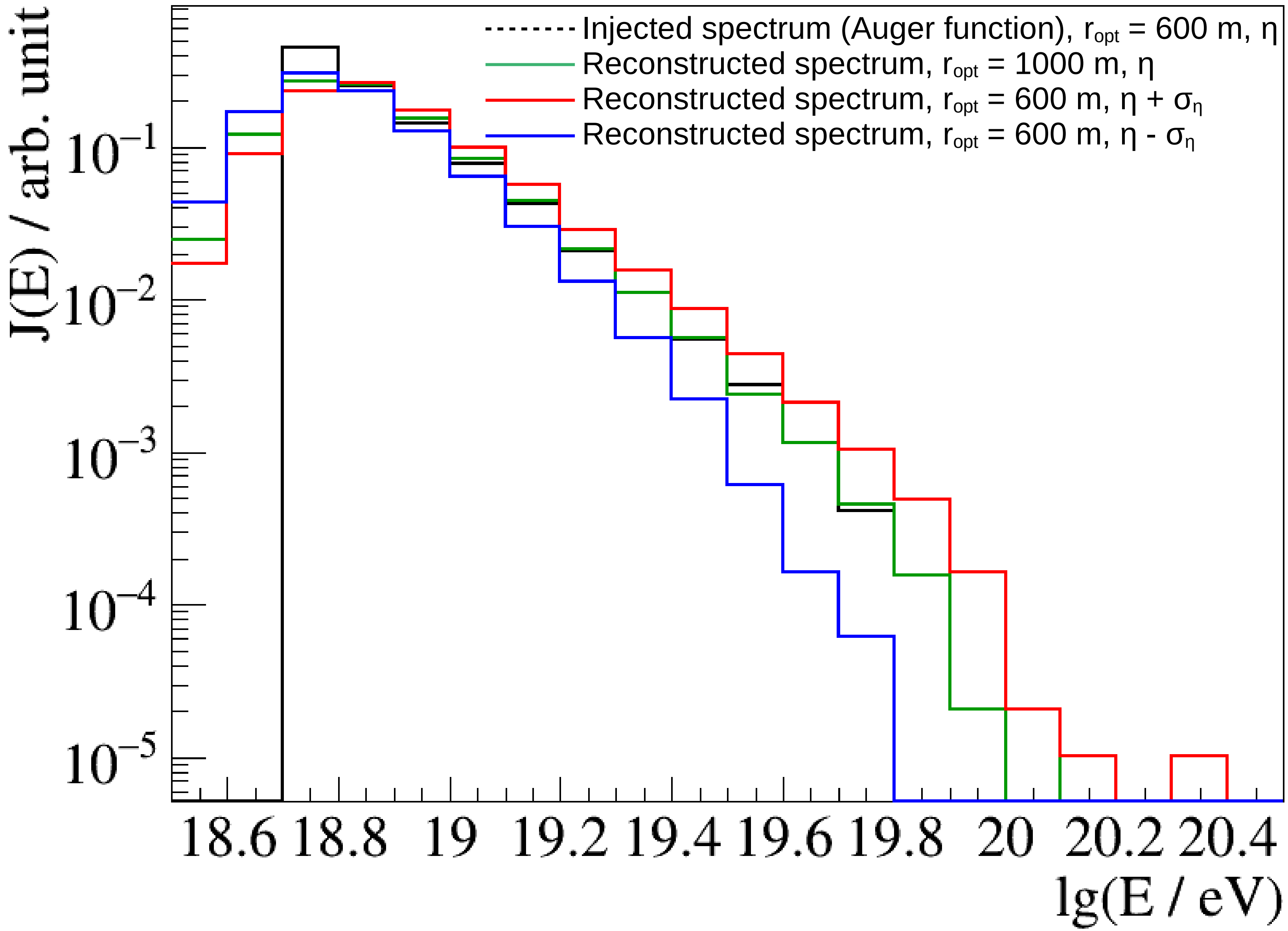
AGASA – Effect on the spectrum

$\sigma_\eta = 0.187$

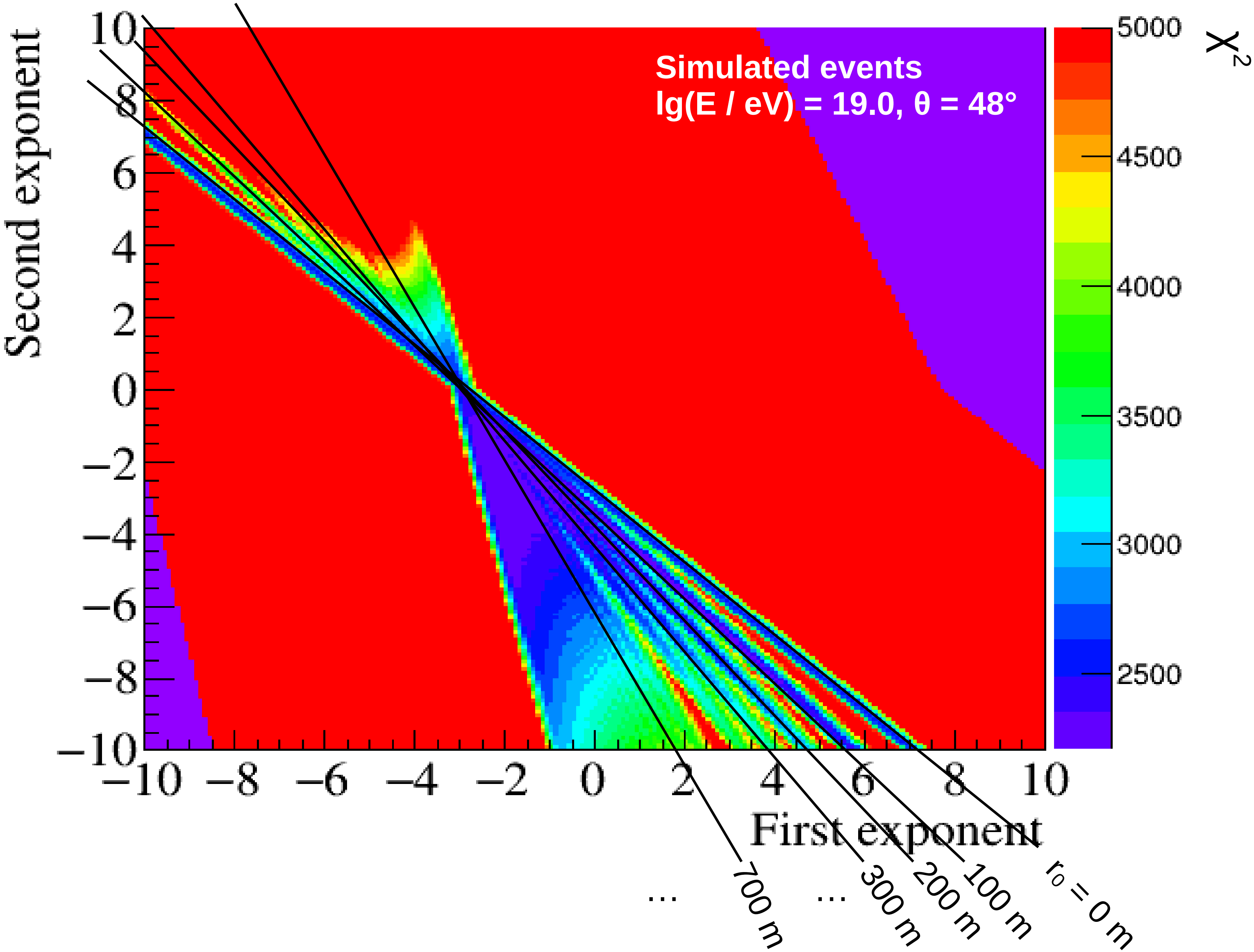


AGASA – Effect on the spectrum

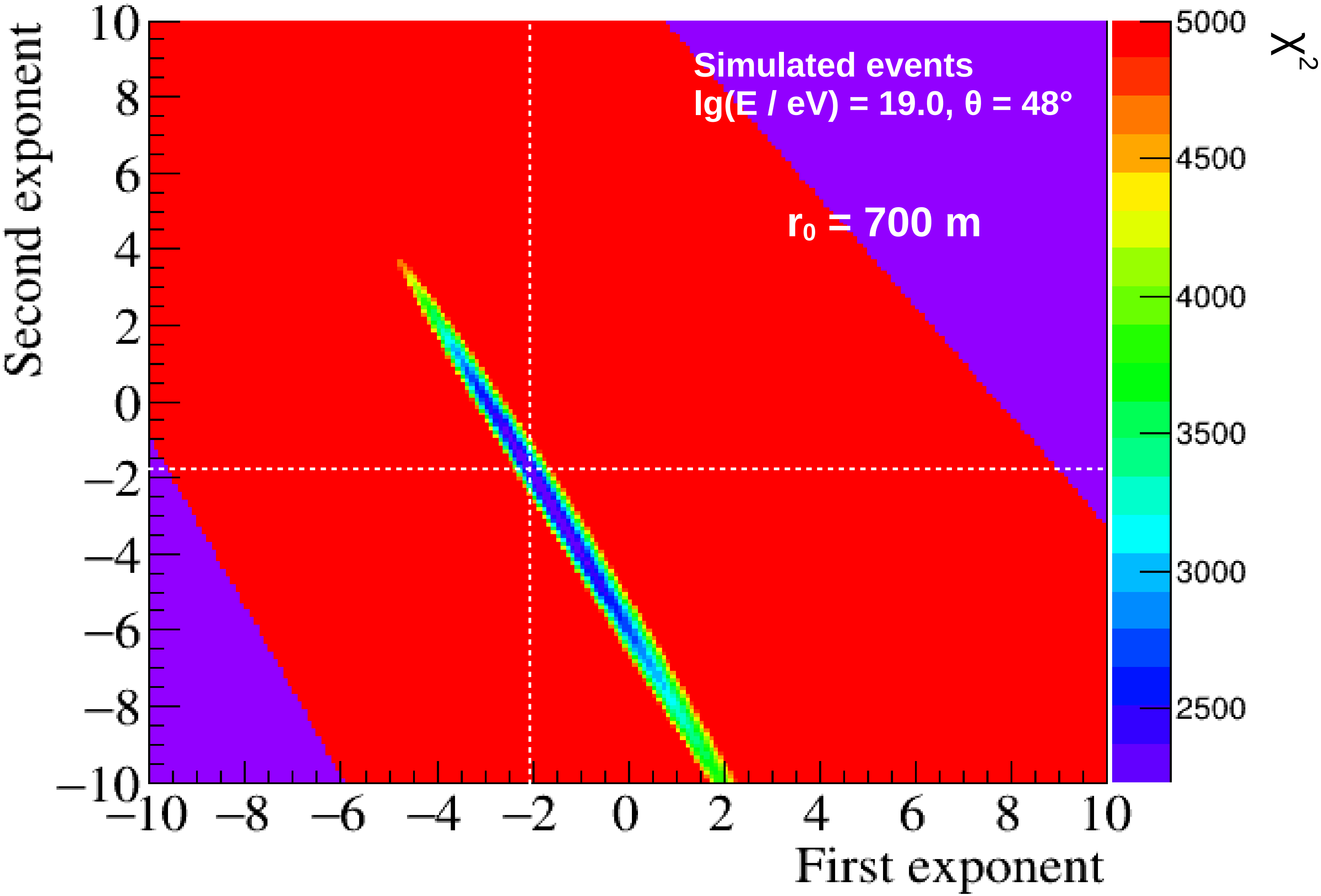
$$\sigma_\eta = \sqrt{0.13^2 + 0.62^2(\sec\theta - 1)^2}$$



Correlation of r_0 and exponents – Auger WCD



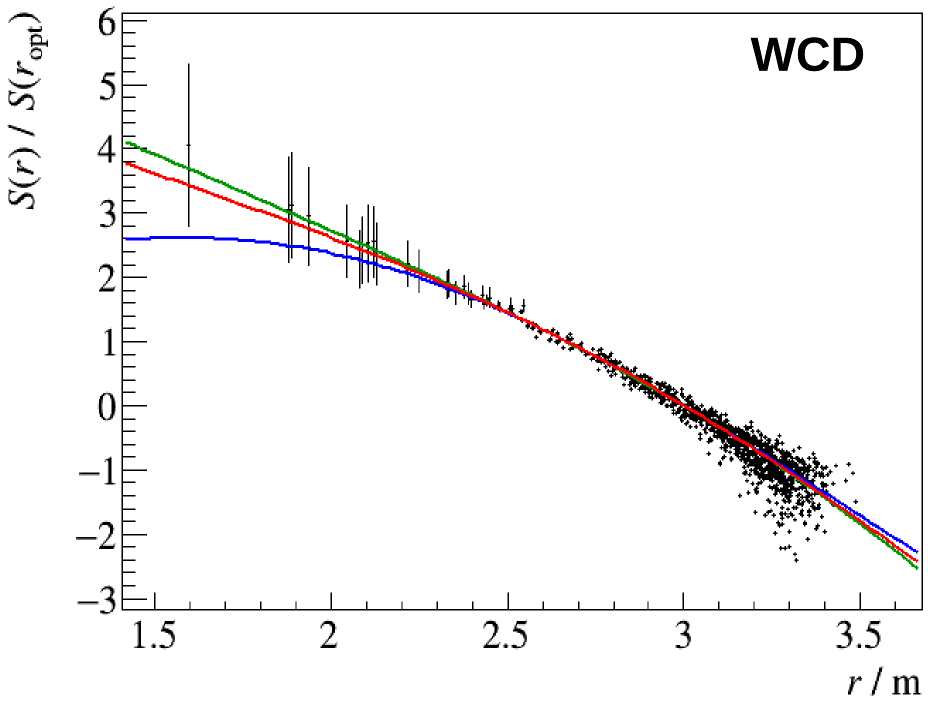
Correlation of r_0 and exponents – Auger WCD



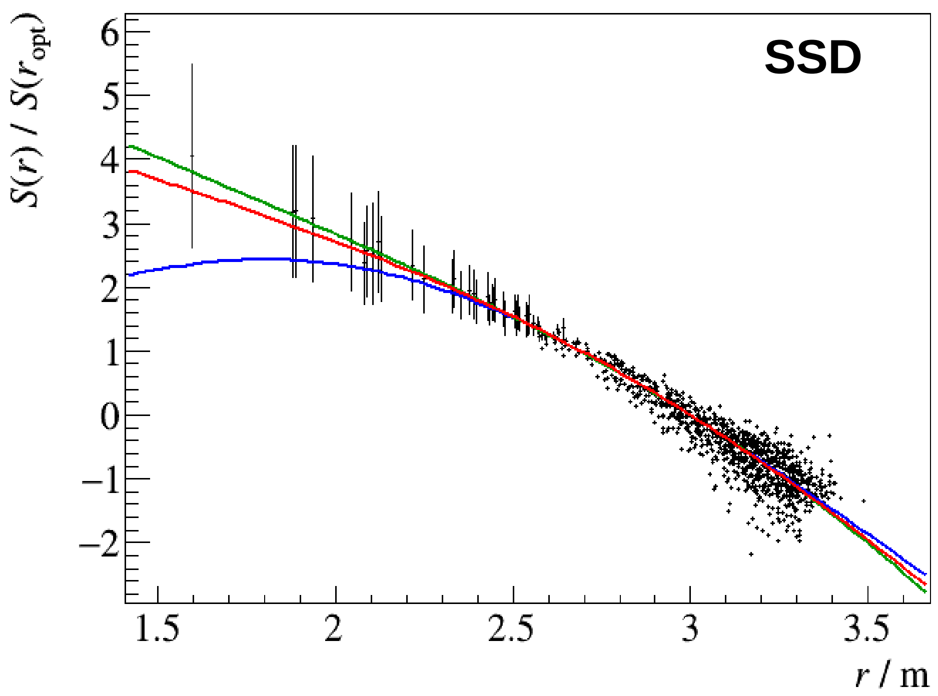
Visualisation of the minima – Auger

Auger-NKG **LDF**
Proton, QGSJet-II.04
lg(E/eV) = 19, θ = 48°
Triangular array, 1500 m

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+r_0}{1000+r_0}\right)^{-\gamma}$$

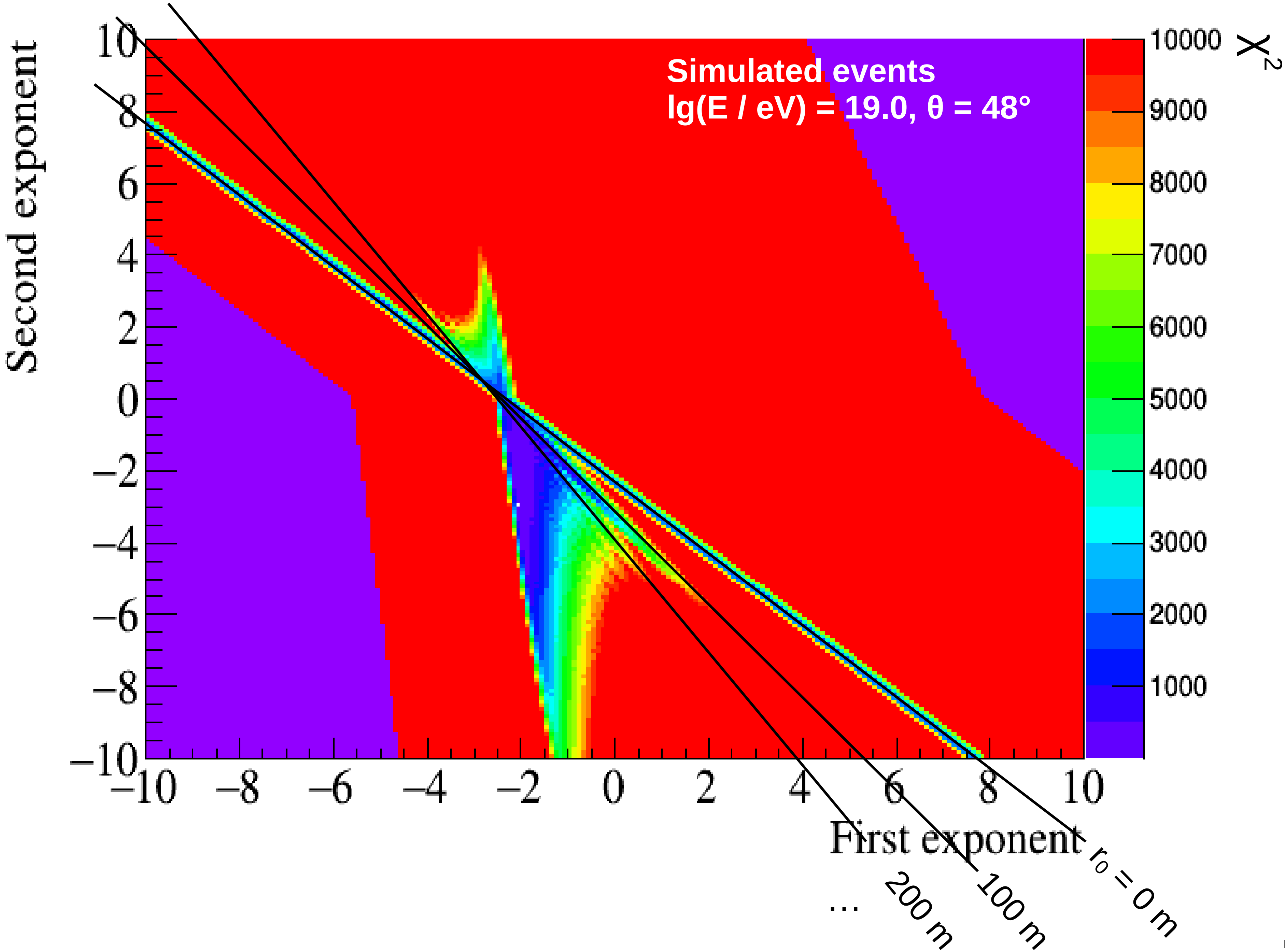


- β = -1.4, γ = 5.1, r_0 = 100 m
- β = 1.8, γ = 2.5, r_0 = 700 m
- β = 2.3, γ = 3.2, r_0 = 2400 m



- β = -2.6, γ = 6.7, r_0 = 100 m
- β = 1.7, γ = 3.1, r_0 = 700 m
- β = 2.3, γ = 4.0, r_0 = 2400 m

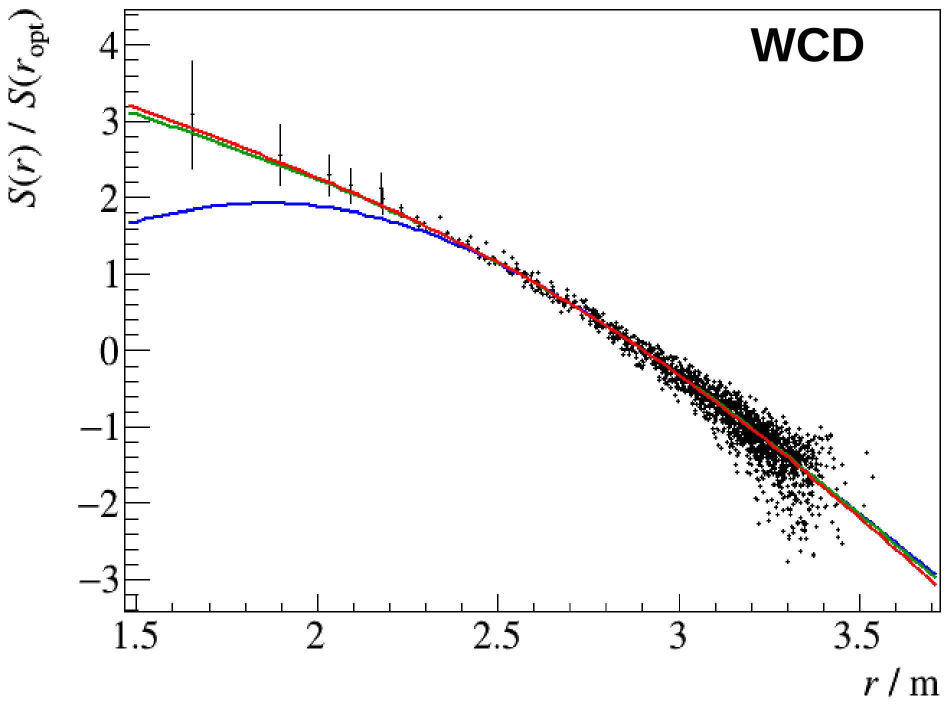
Correlation of r_0 and exponents – TA SSD

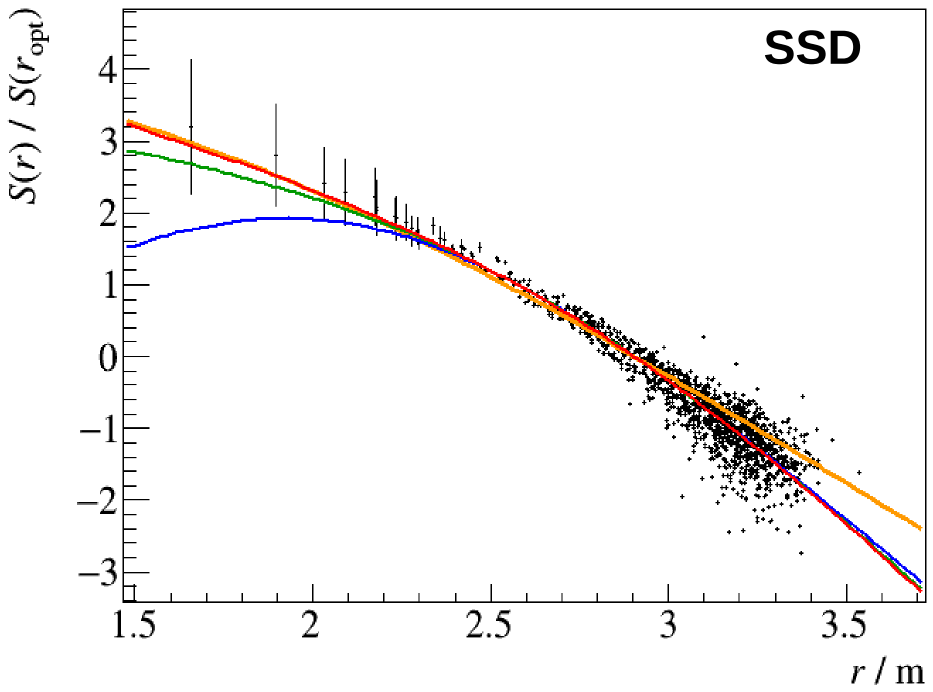


Visualisation of the minima – TA

***AGASA* LDF**
Proton, QGSJet-II.04
lg(E/eV) = 19, θ = 48°
Square array, 1200 m

$$\rho(r) = \rho(800)\left(\frac{r}{800}\right)^{-\alpha}\left(\frac{r+r_0}{800+r_0}\right)^{-(\eta-\alpha)}$$





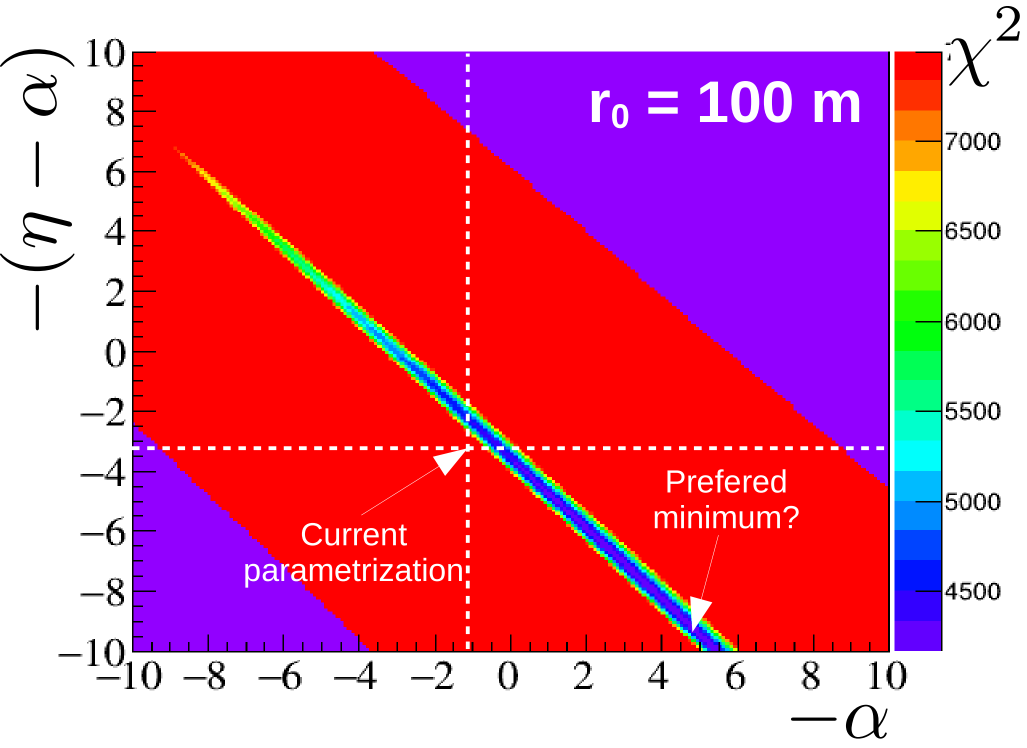
WCD:
- α = -2.9, -(η-α) = 4.0, r_0 = 100 m
- α = 1.4, -(η-α) = 4.3, r_0 = 500 m
- α = 1.6, -(η-α) = 4.6, r_0 = 700 m

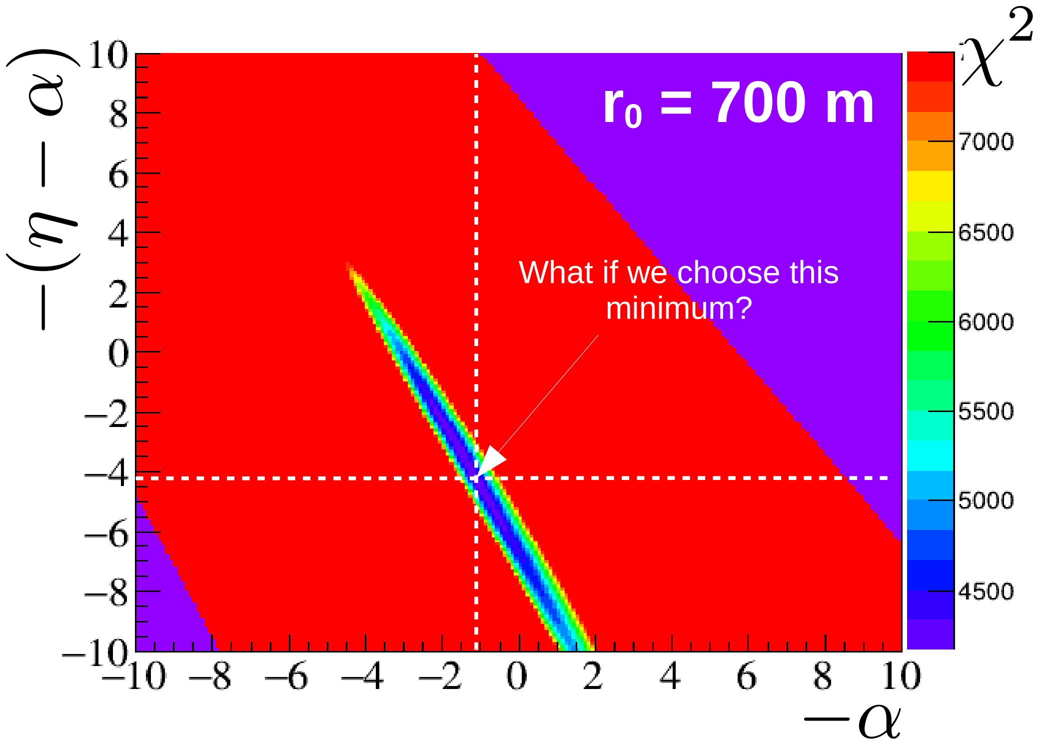
SSD:
- α = -2.9, -(η-α) = 4.0, r_0 = 100 m
- α = 1.4, -(η-α) = 4.3, r_0 = 500 m
- α = 1.6, -(η-α) = 4.6, r_0 = 700 m
- α = 1.2, -(η-α) = 3.08, r_0 = 100 m

Correlation of the parameters of the LDF

SSD, **no saturation,** ***AGASA*** **LDF**
Square, 1200 m
Proton, lg(E/eV) = 19, θ = 48°, QGSJet-II.04

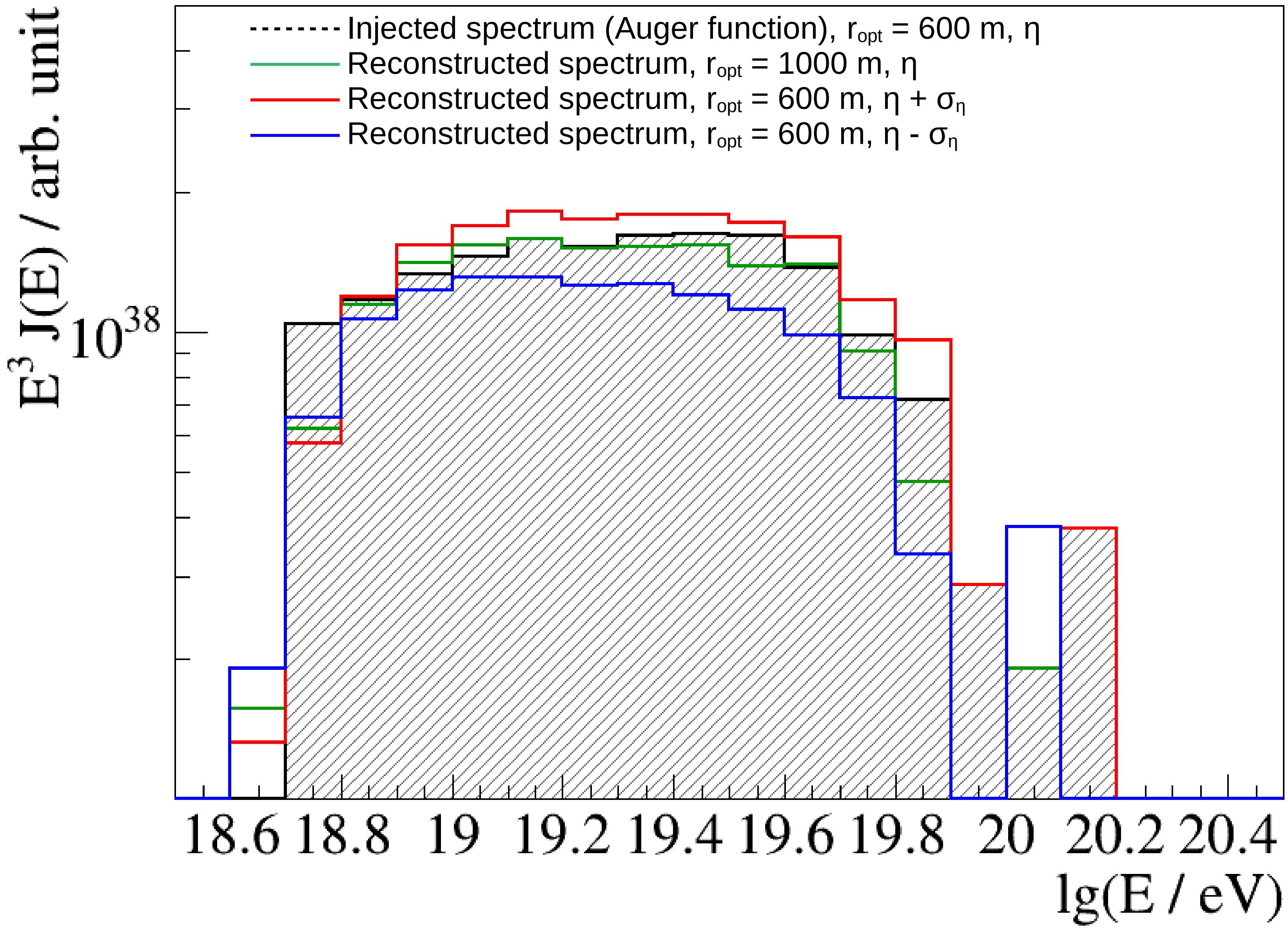
In each energy and zenith bins, using a χ^2, check all sets of (r_0, α, η)





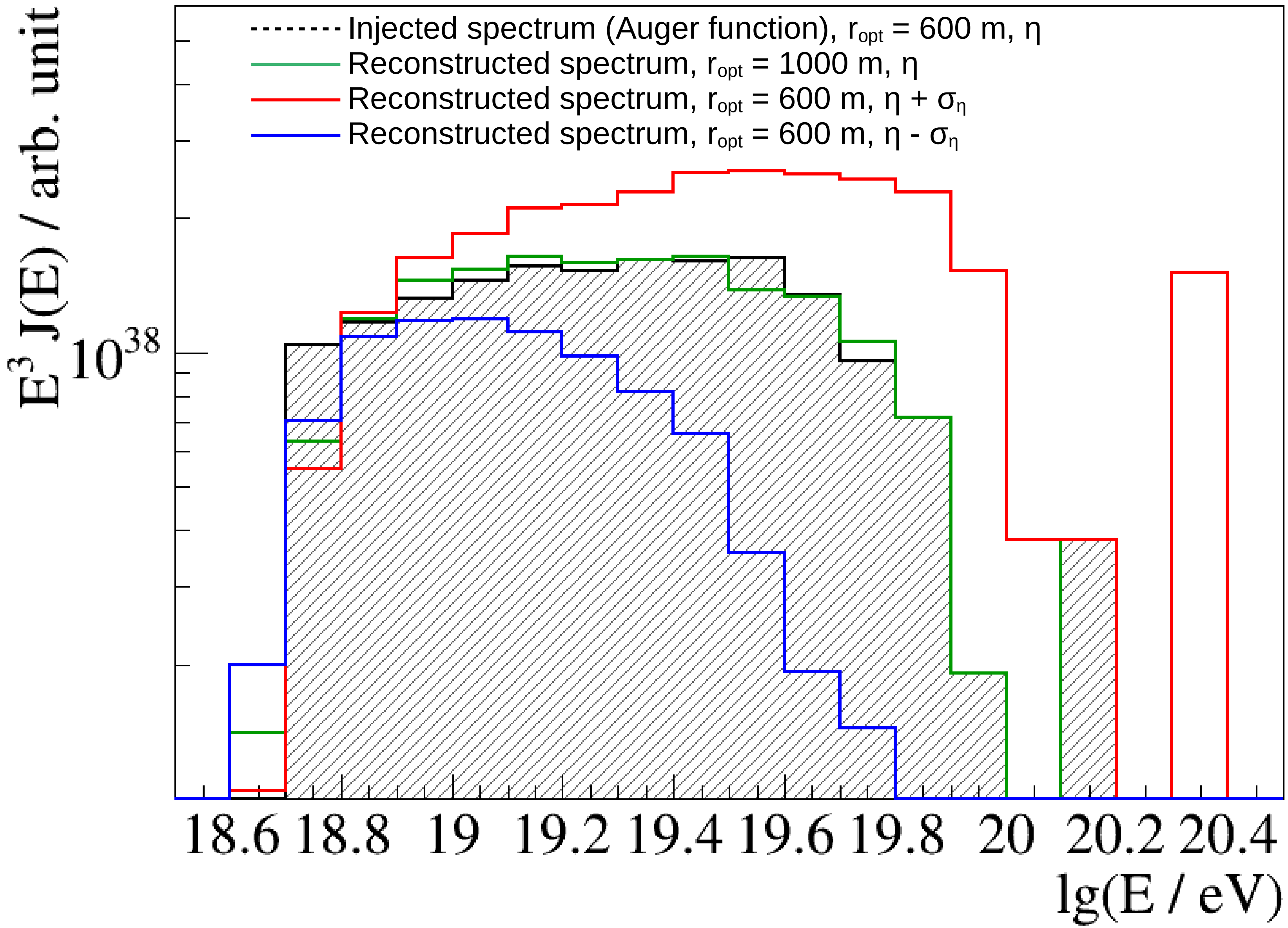
AGASA – Effect on the spectrum

$\sigma_\eta = 0.187$



AGASA – Effect on the spectrum

$$\sigma_\eta = \sqrt{0.13^2 + 0.62^2(\sec\theta - 1)^2}$$



AGASA – Effect on the spectrum