THE COSMIC RAY ENERGY SPECTRUM MEASURED WITH THE PIERRE AUGER OBSERVATORY

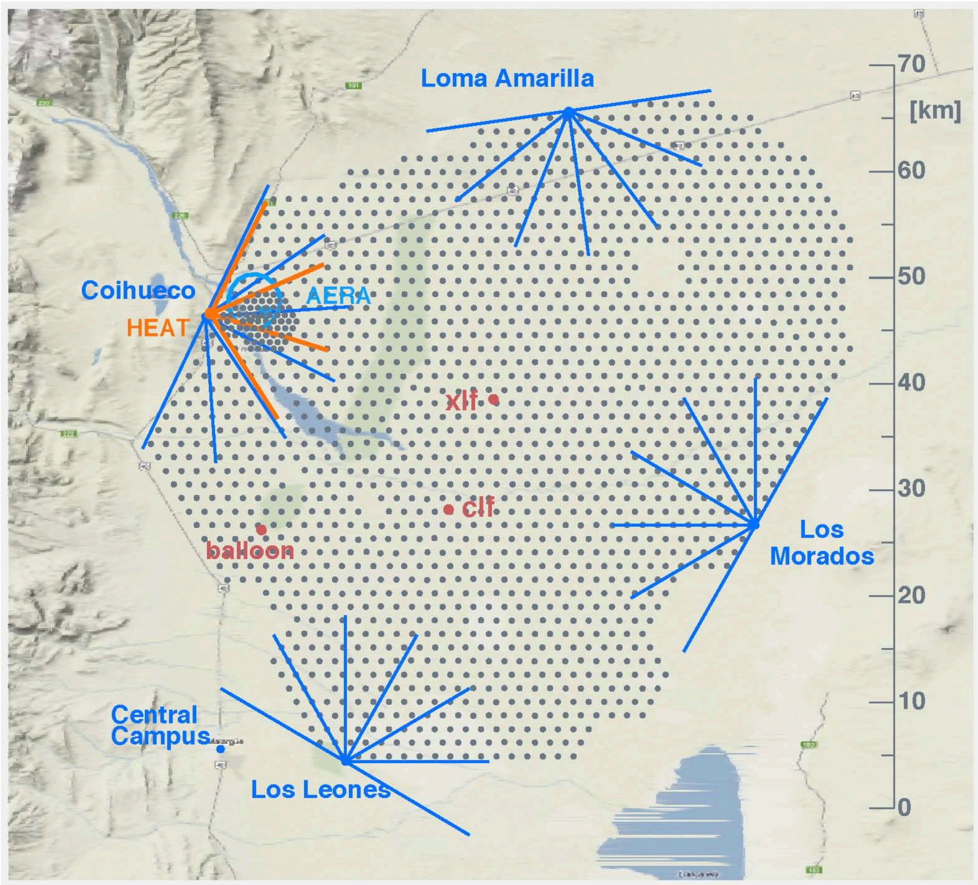
Valerio Verzi
for the Pierre Auger Observatory
INFN, Sezione di Roma "Tor Vergata"

October 8-12, Paris (France)

THE PIERRE AUGER OBSERVATORY

NIM A 798 (2015) 172-213

Malargüe – Mendoza (Argentina)
35^0 S latitude 3000 km^2



Surface detector (SD)
-1500 m grid of 1600 water cherenkov detectors
- 750 m grid (24 km^2) with 61 additional stations

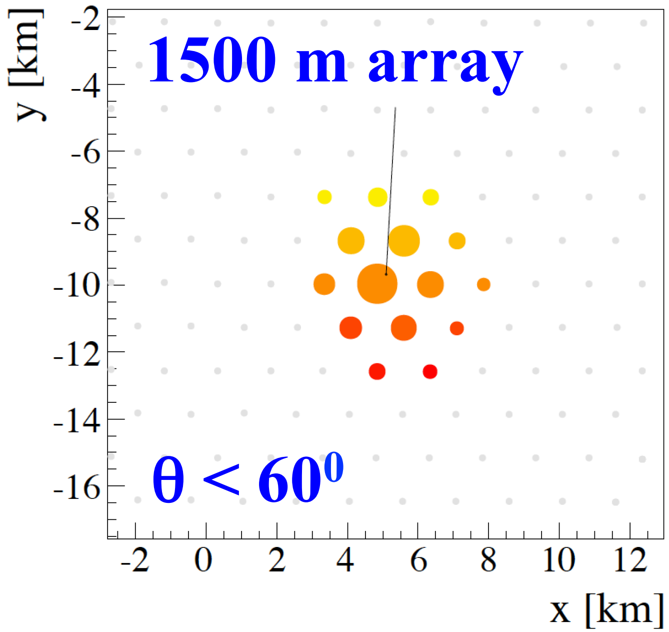
Fluorescence detector (FD)
- 24 telescopes (0^0-30^0)
- 3 telescopes (30^0-60^0)

Hybrid Observatory
energy scale set with the FD

AUGER EVENTS

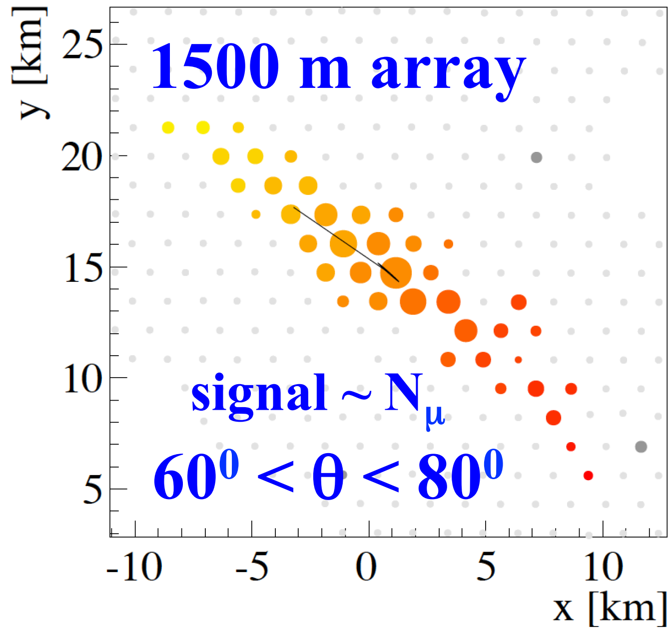
SD vertical

energy thr.
3 EeV



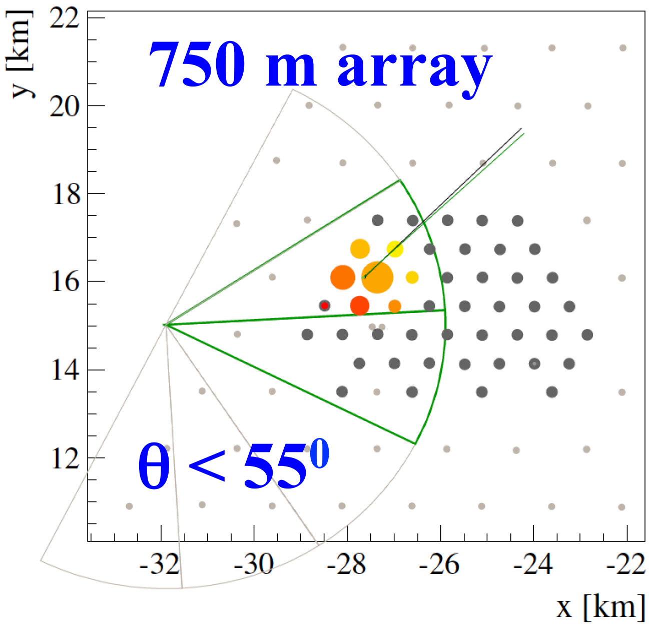
SD Inclined

energy thr.
4 EeV



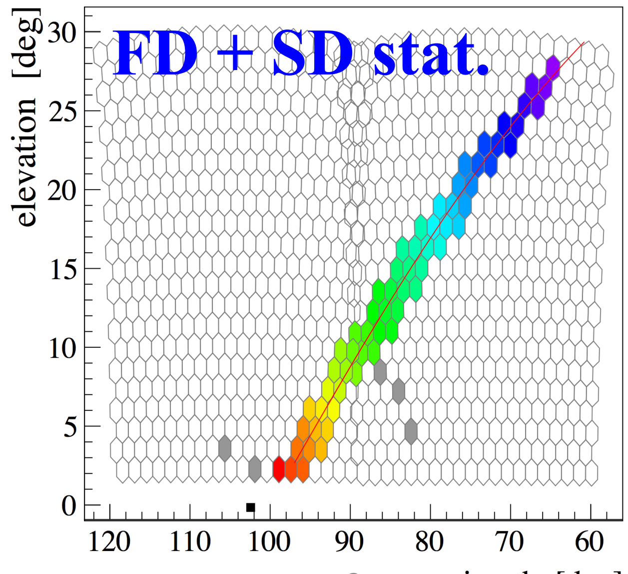
SD infill

energy thr.
0.3 EeV

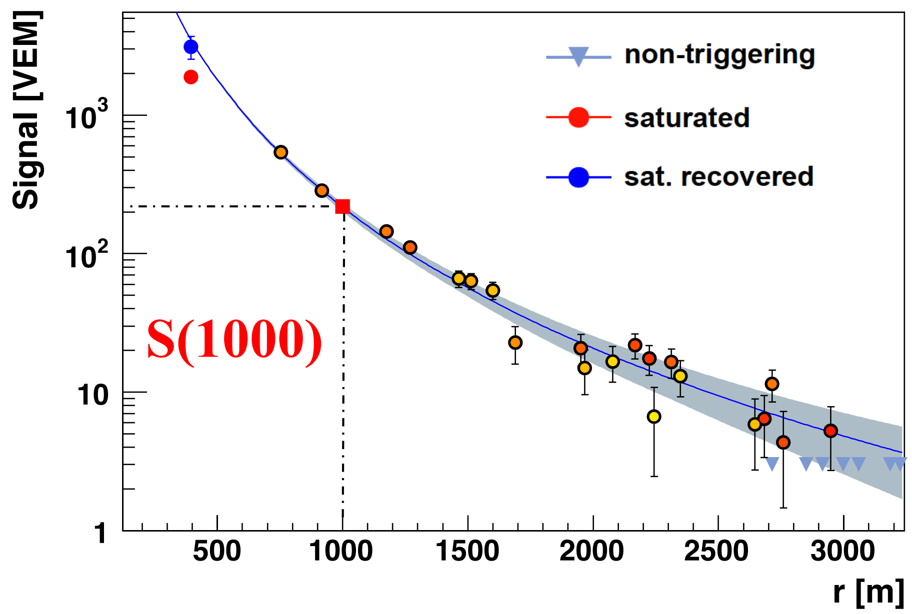


hybrid
13% duty cycle

energy thr.
1 EeV



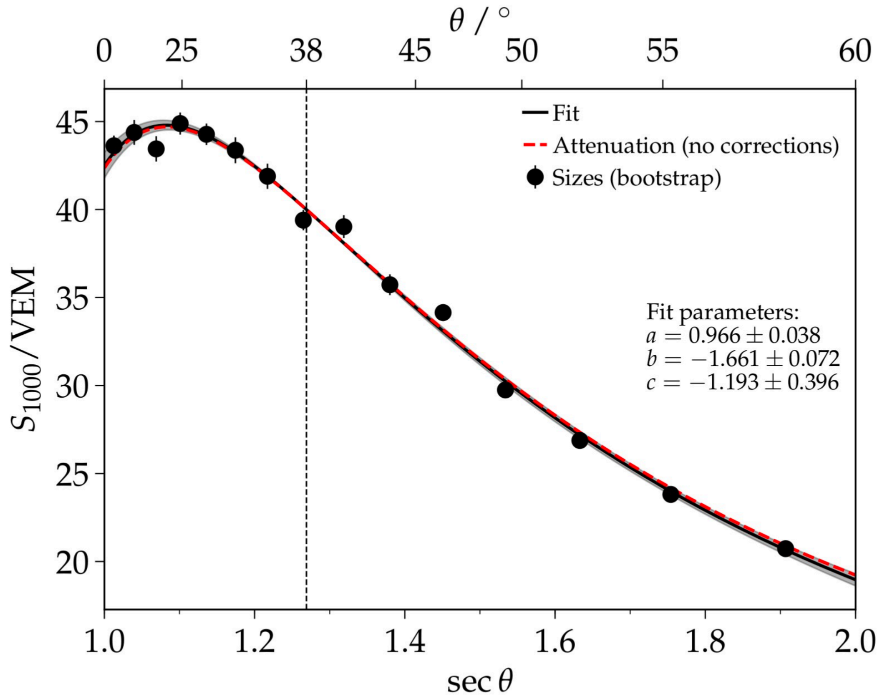
SD ENERGY ESTIMATOR (vertical events)



fit the lateral distribution of the signals to get S(1000)

use the CIC method to remove the zenith angle dependence of S(1000)

➡ S_{38}



similar method for the 750m array (S(450) → S_{35})

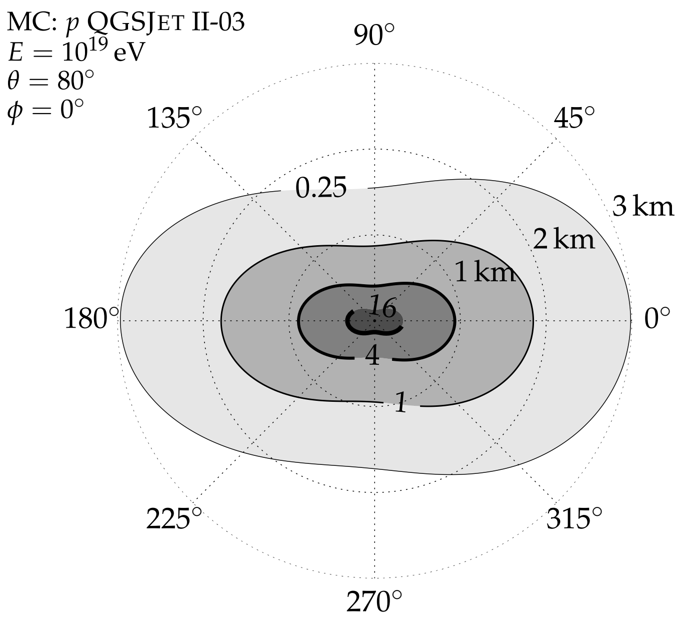
correction determined from data (no use of simulations)

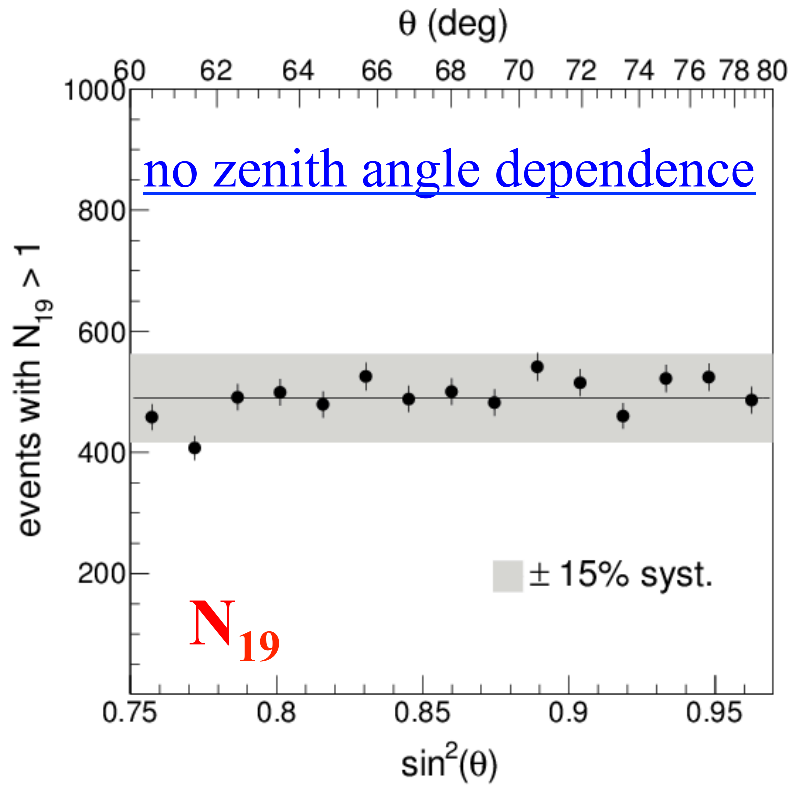
SD ENERGY ESTIMATOR (inclined events)

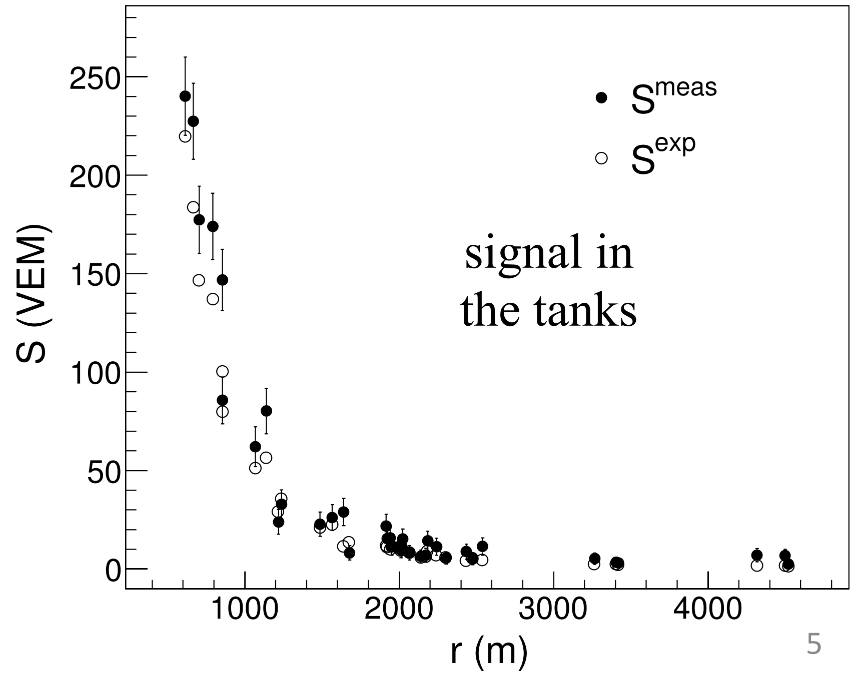
JCAP 08 (2014) 019

use muons density maps to get the energy estimator

$$\rho_\mu = N_{19}\ \rho_{\mu,19}(r,\theta,\phi)$$







FD EVENTS

$$n_{ADC} \sim \frac{dE}{dX} Y_{flu} \; T_{atm} C_{calib}$$

Fluorescence yield

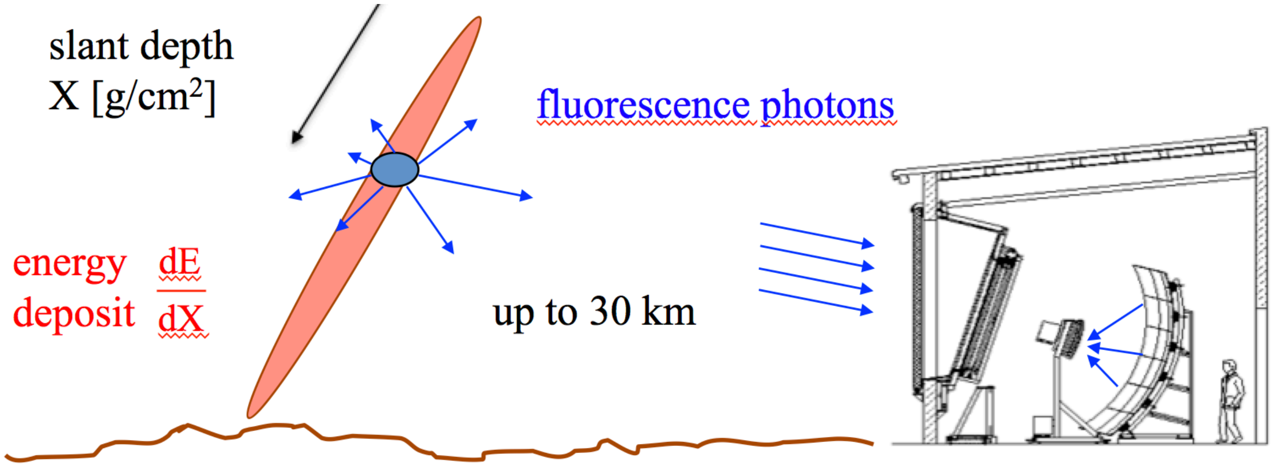
Atmosphere

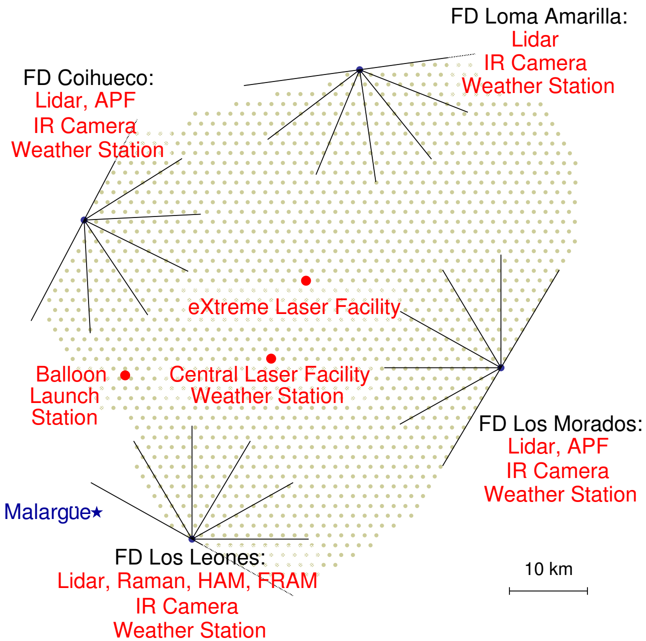
FD calibration

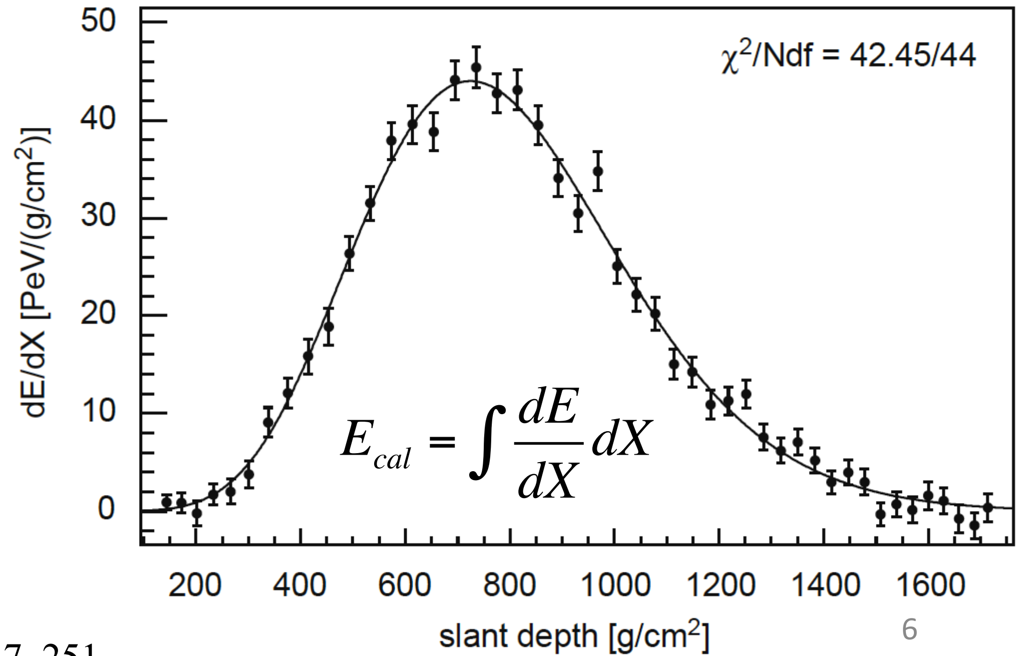
dE/dX reconst.

Invisible energy (ν, μ, ..)

$$E = E_{cal} + E_{inv}$$







$$E_{cal} = \int \frac{dE}{dX} dX$$

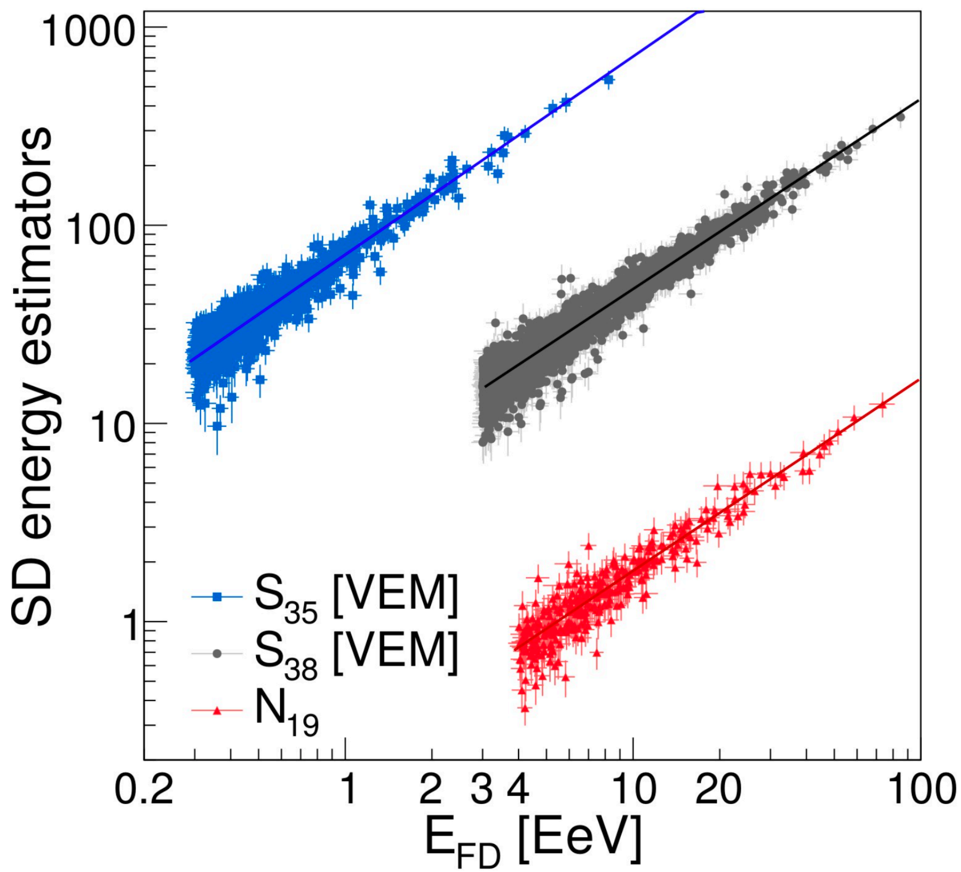
Auger, Astrop. Phys. 33 (2010) 108 NIM A 620 (2010) 227–251

CALIBRATION OF THE SD ENERGY ESTIMATORS

data sample
(Jan 2004 – Dec 2015)

- high quality hybrid events
- above the saturation of the SD trigger efficiency

$$E = A\, S^B \quad B \approx 1$$



ICRC 2017	1500 m		750 m
Zenith angle range [deg.]	0 - 60	60 - 80	0 - 55
Energy threshold	3×10^{18} eV	4×10^{18} eV	3×10^{17} eV
Number of events	2661	312	1276
A	(0.178 ± 0.003) EeV	(5.45 ± 0.08) EeV	(14.1 ± 0.4) PeV
B	1.042 ± 0.005	1.03 ± 0.02	1.000 ± 0.008
Energy resolution [%]	15	19	13

ENERGY SCALE

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	**0.5% ÷ 1.5%**
Stability of the energy scale	**5%**
TOTAL	**14%**

FY: high precision measurements of Airfly

good control atmospheric cond. (aerosols: L.Valore, this conf.)

FD calib.: largest contribution (not energy dependent)

data-driven estimation of the invisible energy (A. Mariazzi, this conf.)

Total uncertainty 14%

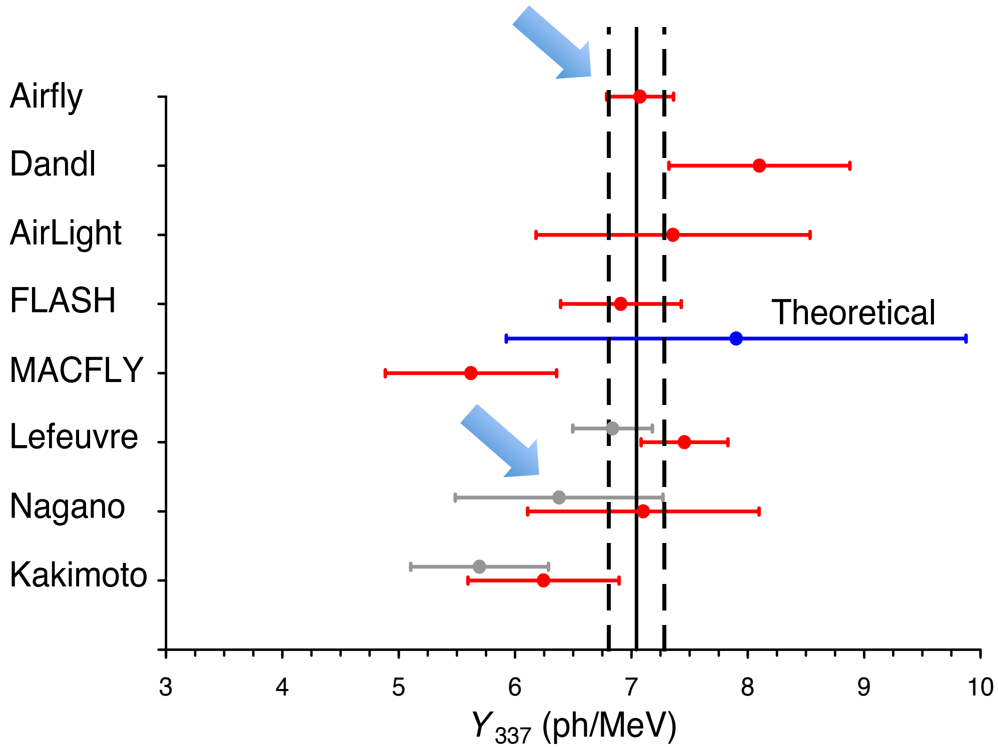
ENERGY SCALE

<u>14% uncertainty mainly thanks to Airfly</u>

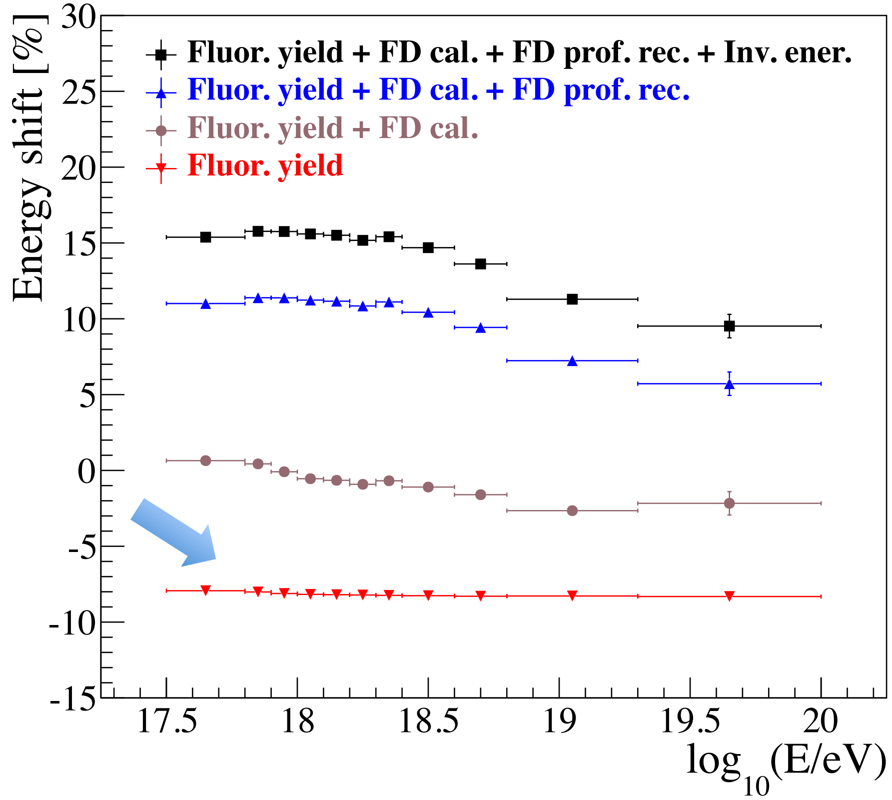
M. Ave et al., Astropart. Phys. 28 (2007) 41

Before 2013 we used Nagano and it was 22%

note: from Nagano to Airfly -8% energy shift !



J. Rosado et al., Astropart. Phys. 55 (2014) 51



note: > 20% difference between Airfly and Kakimoto (TA)

ENERGY SCALE

data-driven estimations of the invisible energy

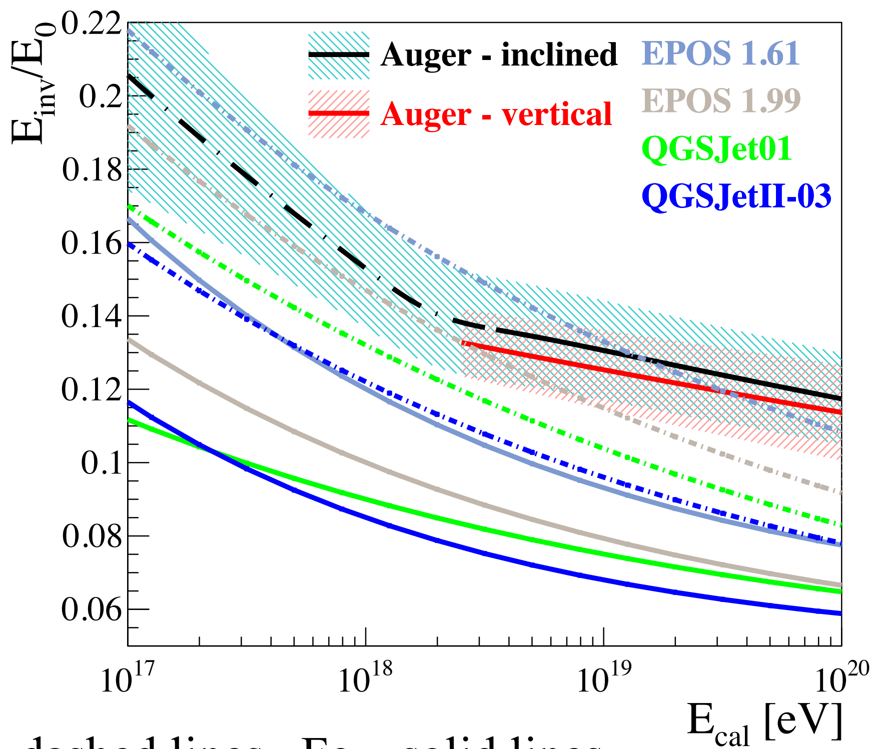
$$E_{\text{inv}} = \epsilon_c^\pi N_\mu = \epsilon_c^\pi \beta_0 \left(\frac{E_0}{\epsilon_c^\pi}\right)^\beta$$

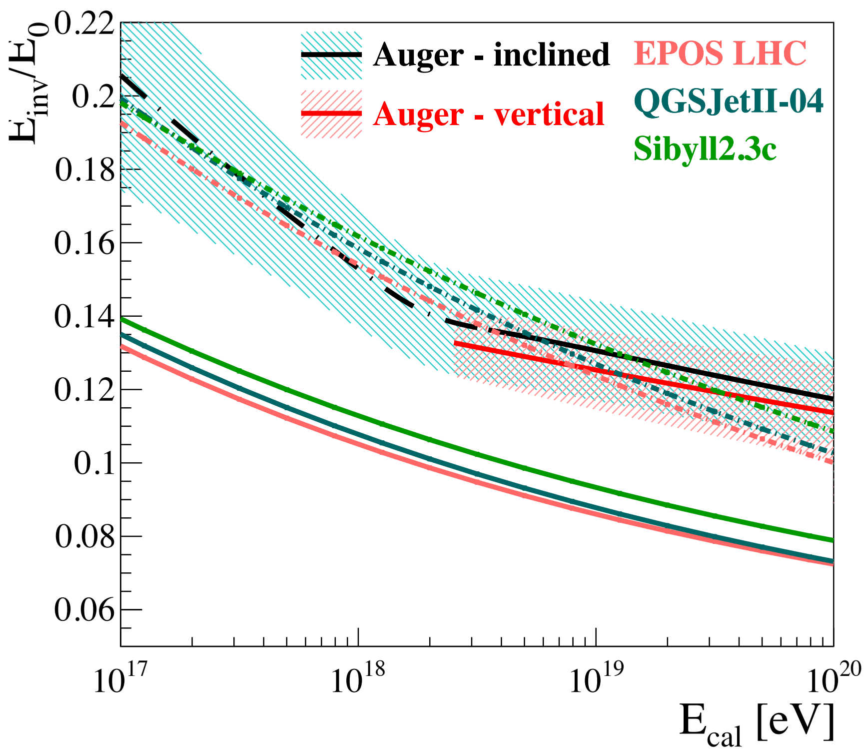
(Matthews-Heitler)

A. Mariazzi, this conf.

inclined showers — vertical showers

note: E_{inv} larger than model predictions as a consequence of the μ number excess (H. Debinski, this conf.)





p – dashed lines   Fe – solid lines

OTHER ADVANTAGES OF THE HYBRID DETECTION TECHNIQUE

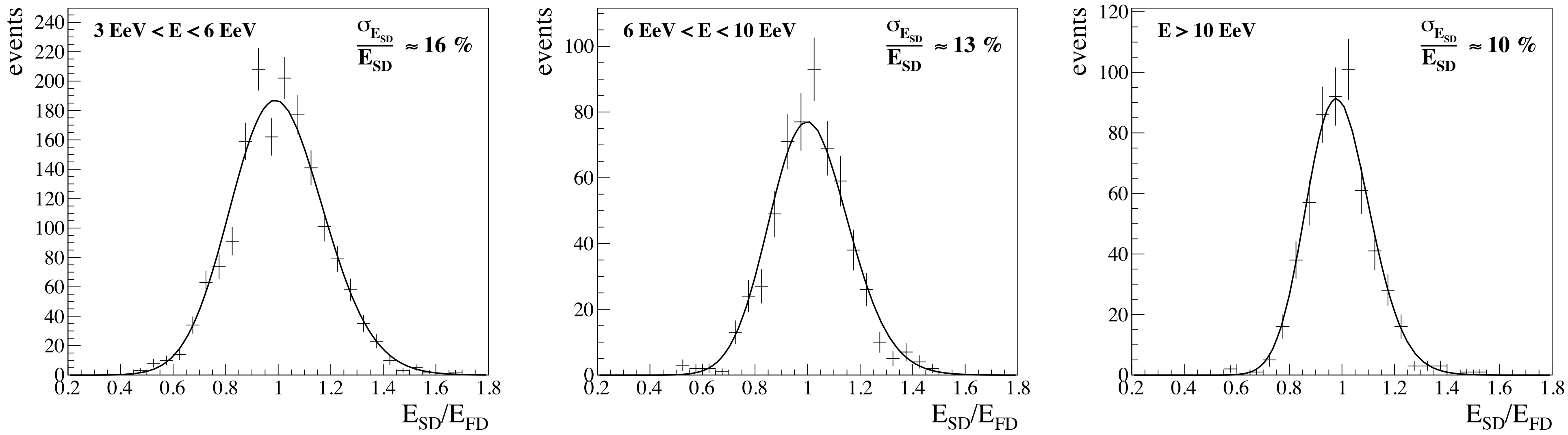
FD 'uncorrelated' uncertainties

ICRC 2013 - arXiv:1307.5059

Aerosol optical depth	**3% ÷ 6%**
Horizontal uniformity of aerosols	**1%**
Atmosphere variability	**1%**
Nightly relative calibration	**3%**
Statistical error of the profile fit	**5% ÷ 3%**
Uncertainty in shower geometry	**1.5%**
Invis. En. (shower-to-shower fluc.)	**1.5%**
Total FD energy resolution	**7% ÷ 8%**

E_{SD} resolution from E_{SD}/E_{FD} distributions knowing the resolution on E_{FD}

not trivial too guarantee a good E_{FD} res. (e.g.: hourly meas. of aerosols)

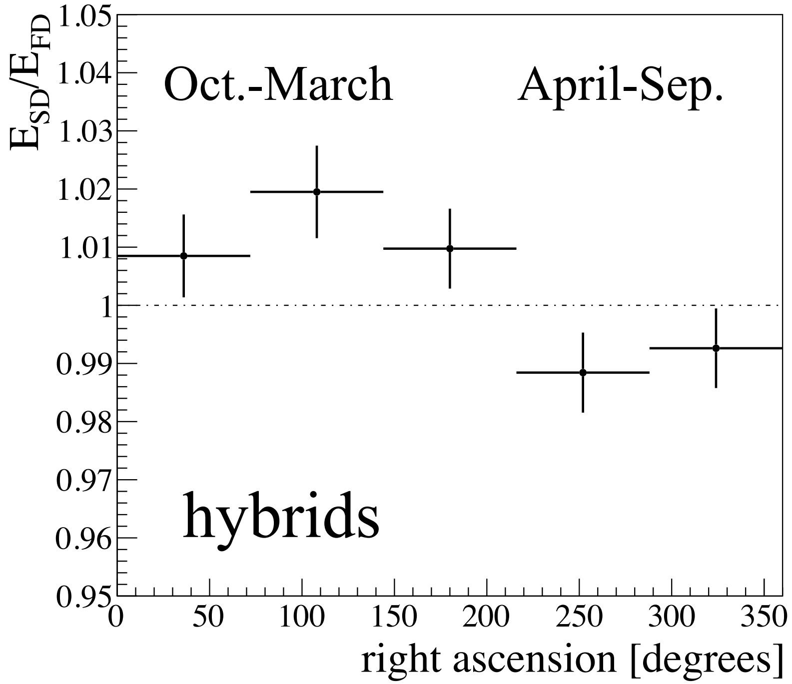


time dependence of the FD calibration not perfectly tracked in time

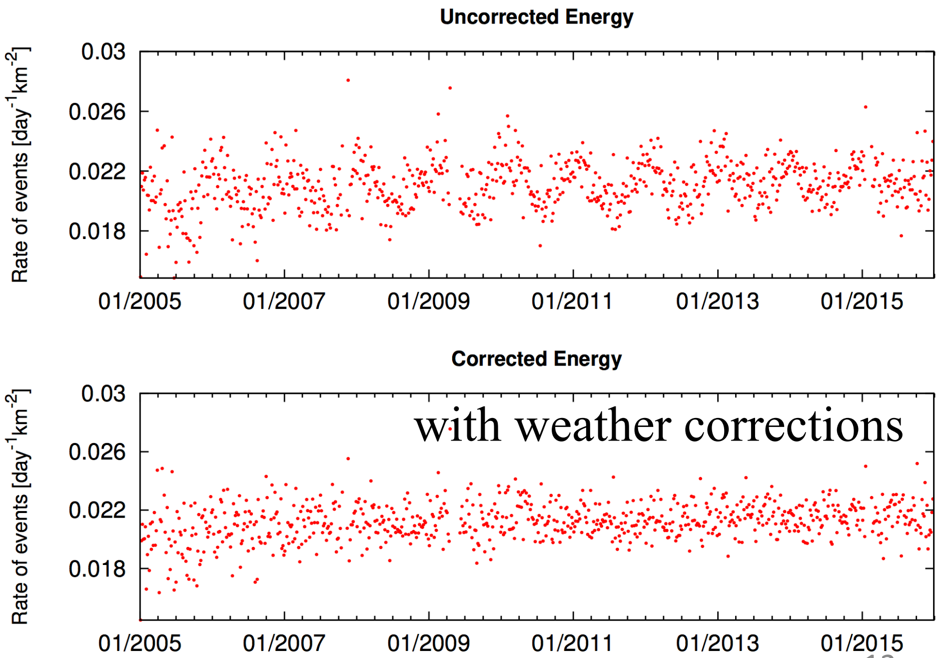
→ affects both systematics and resolution

Sub total (Fluorescence Yield)	3.6%
Sub total (Atmosphere)	3.4% ÷ 6.2%
Sub total (FD calibration)	9.9%
Sub total (FD profile rec.)	6.5% ÷ 5.6%
Invisible energy	3% ÷ 1.5%
Statistical error of the SD calib. fit	0.5% ÷ 1.5%
Stability of the energy scale	5%
TOTAL	14%

e.g.: small modulation due to E_{FD}



rate (SD) vs time for E_{SD} > 2 EeV



JINST 12 P02006 (2017)

ENERGY SPECTRUM: 1500 m vertical

from Jan 2004
to Dec 2016

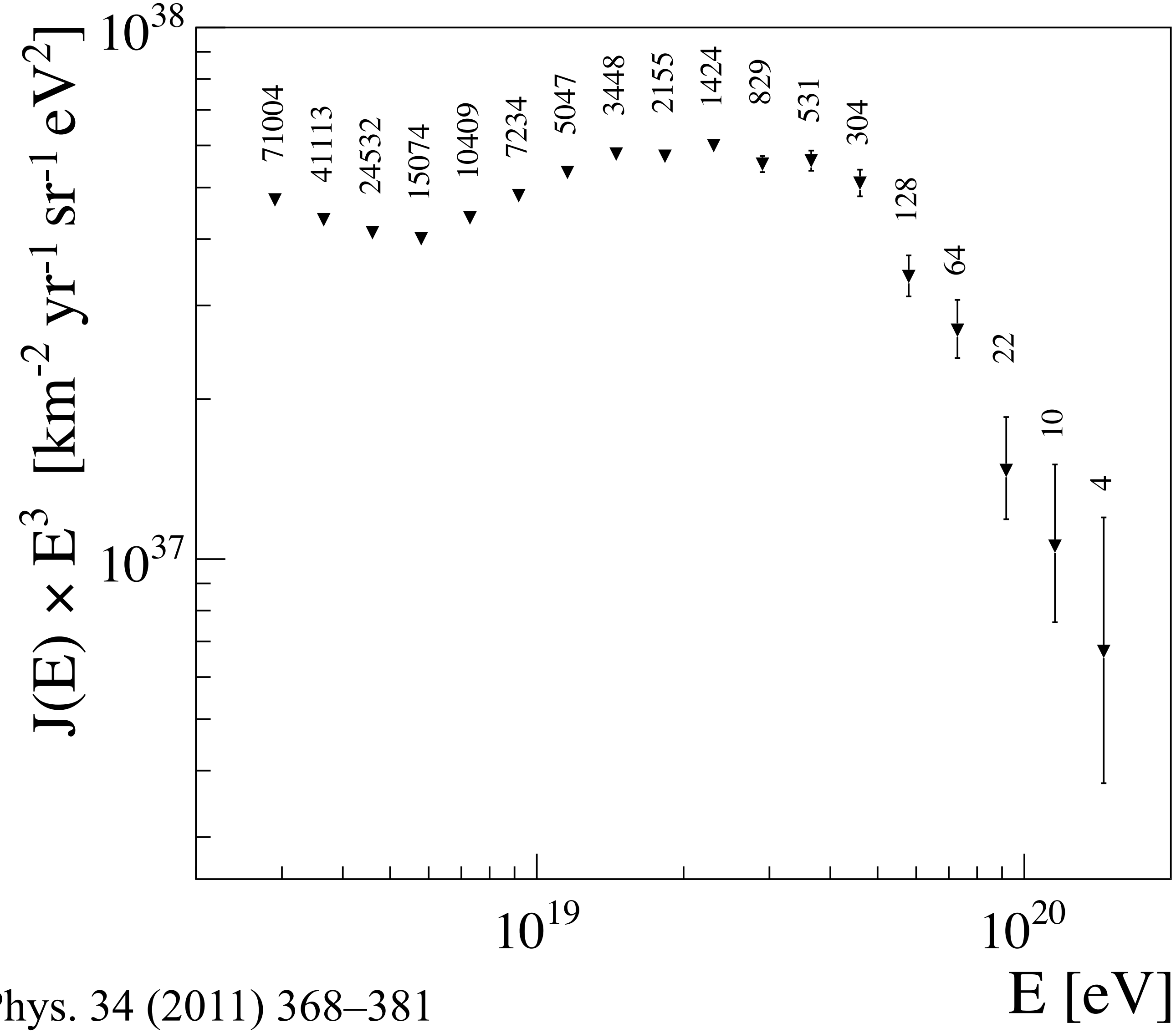
183332 events
$E > 10^{18.4}$ eV

exposure
51588 km^2 yr sr

$$J_{raw} = \frac{N}{\varepsilon}$$

$$\frac{\Delta\varepsilon}{\varepsilon} \approx 3\%$$

‘raw’ spectrum



Astrop. Phys. 34 (2011) 368–381

ENERGY SPECTRUM: 1500 m vertical

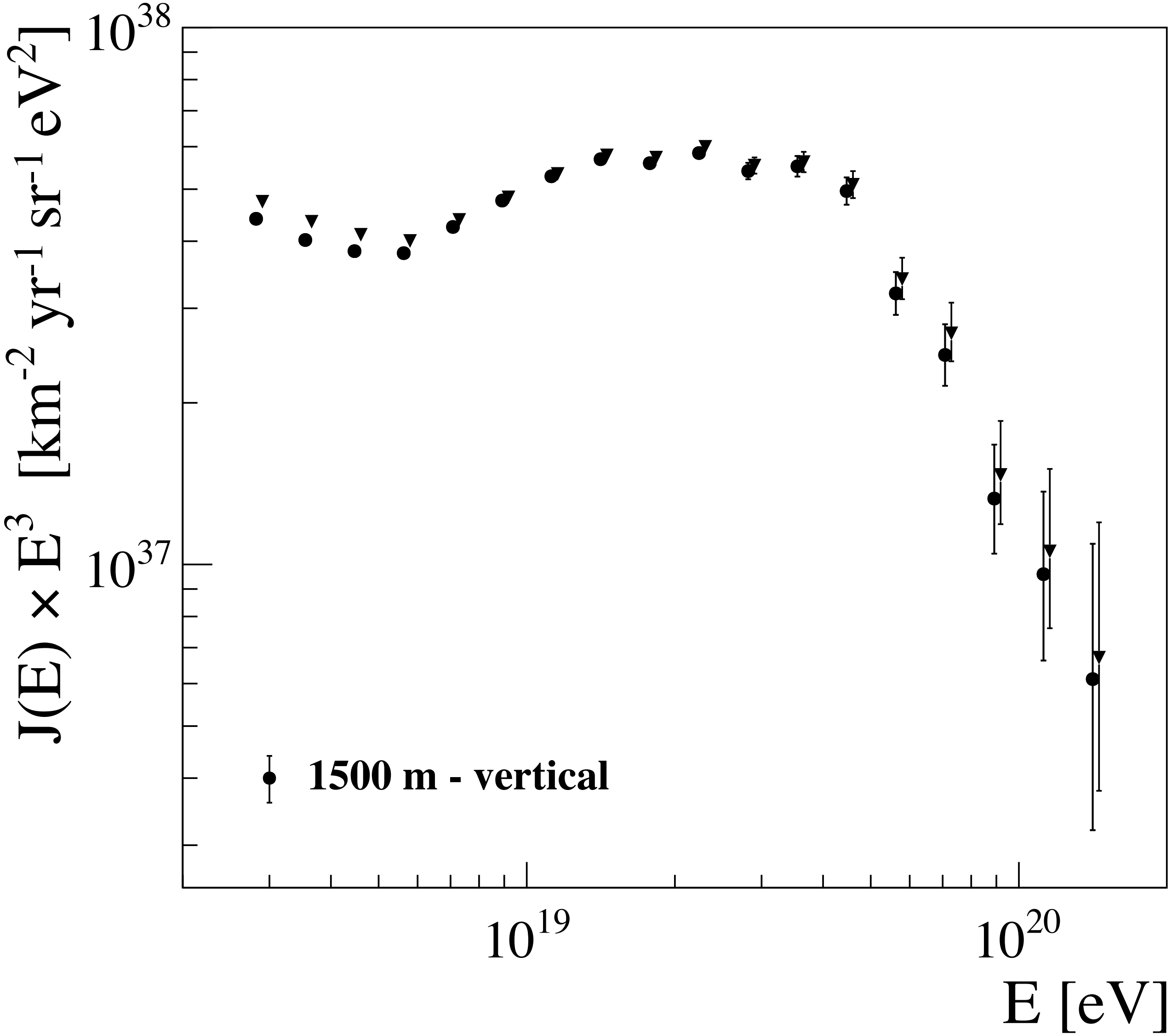
correction for the SD energy resolution

forward folding

(no assumption on spectral parameters)

$$J_{raw} = \frac{N}{\varepsilon}$$

$$J = \frac{N}{\varepsilon} f$$



<u>correction less than 10% (f > 0.9)</u>

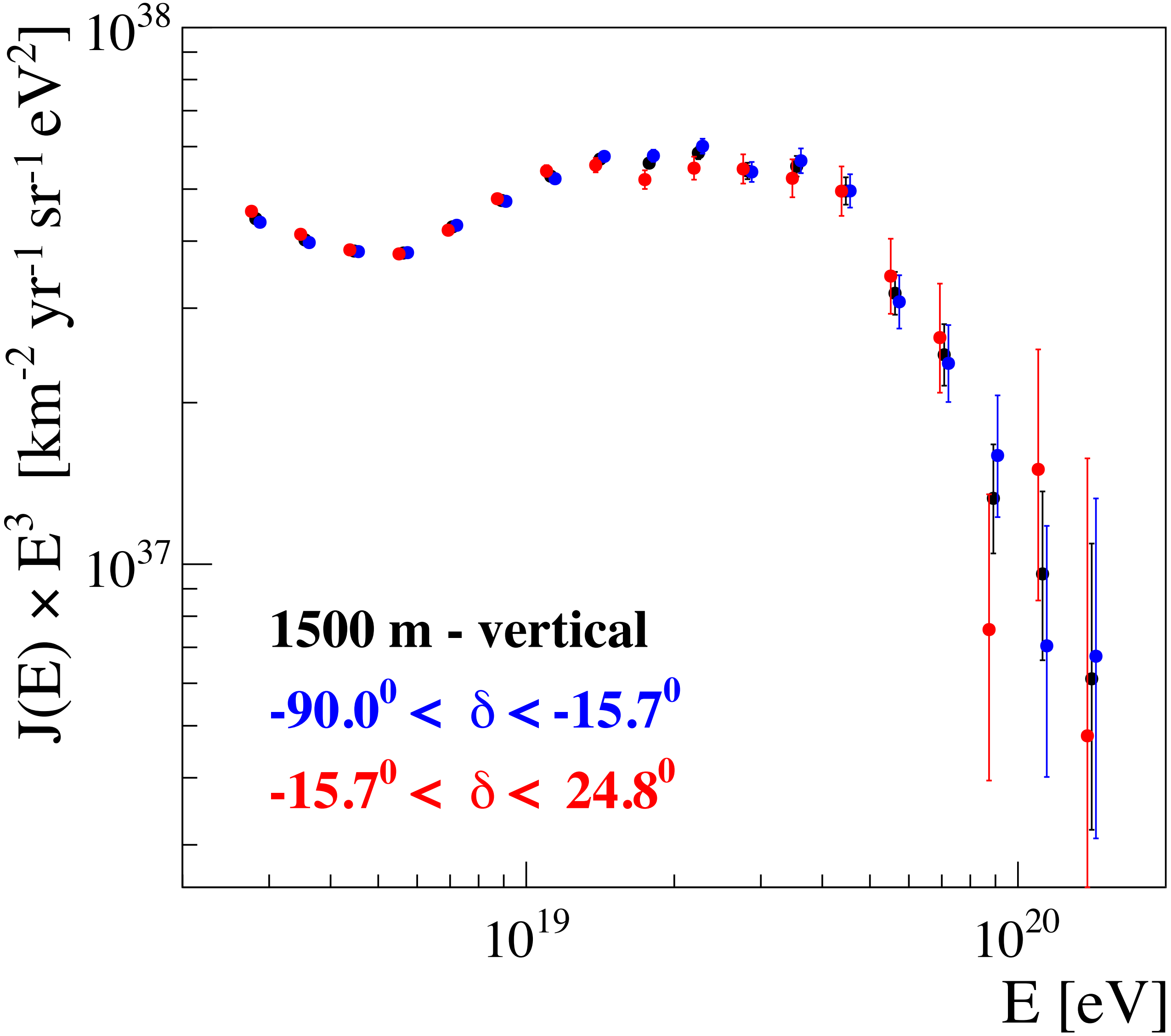
ENERGY SPECTRUM: 1500 m vertical

$-90^0 < \delta < -15.7^0$
123827 events
35117 km^2 sr yr

$-15.7^0 < \delta < 24.8^0$
59505 events
16471 km^2 sr yr

30% of the total exposure in the band common to TA
(D. Ivanov, this conf.)

declination dependence



note: same unfolding correction as in the full band

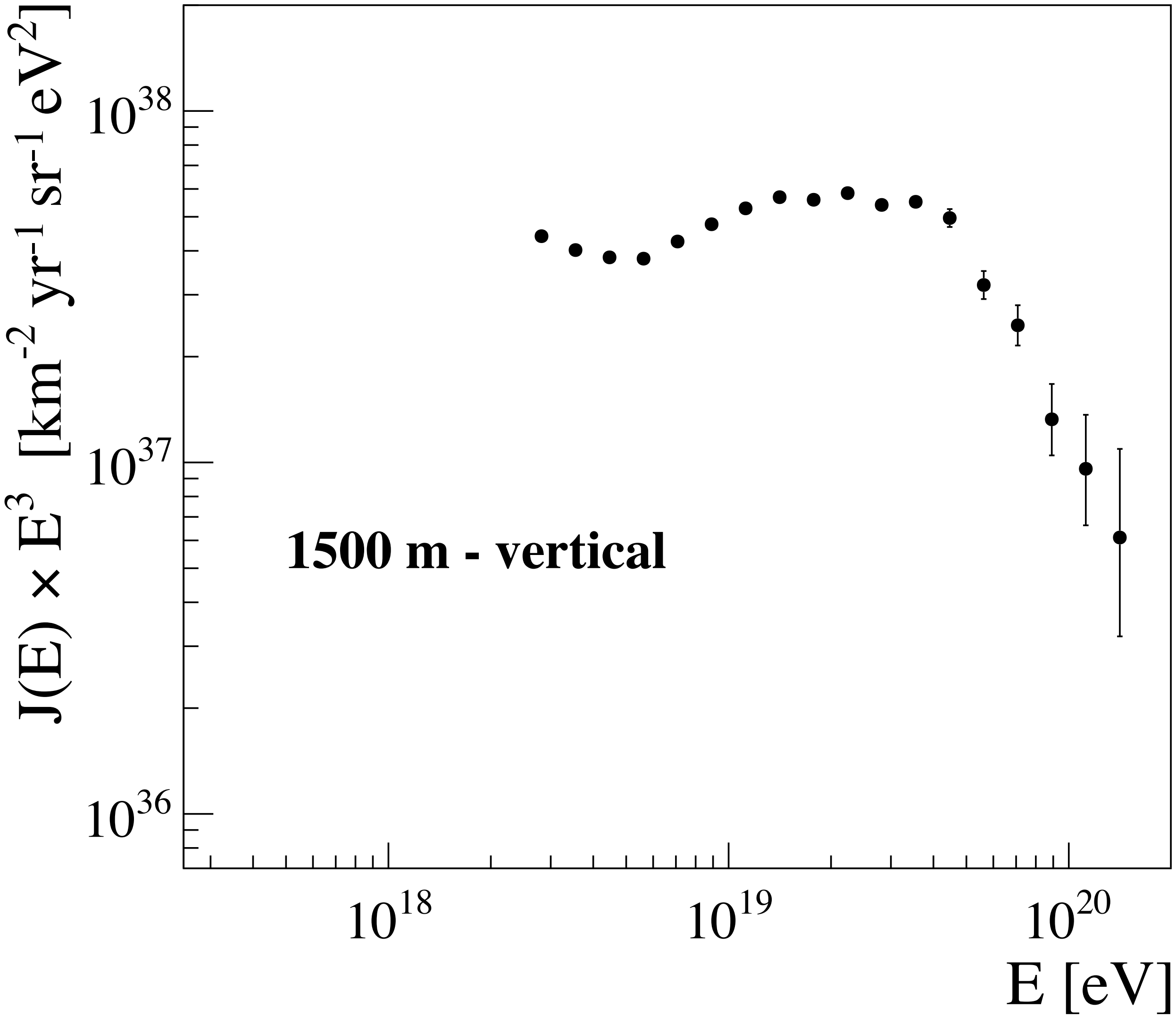
1500 m vertical

183332 events $E > 10^{18.4}$ eV

51588 km^2 yr sr

$\Delta J/J \sim 5\%$

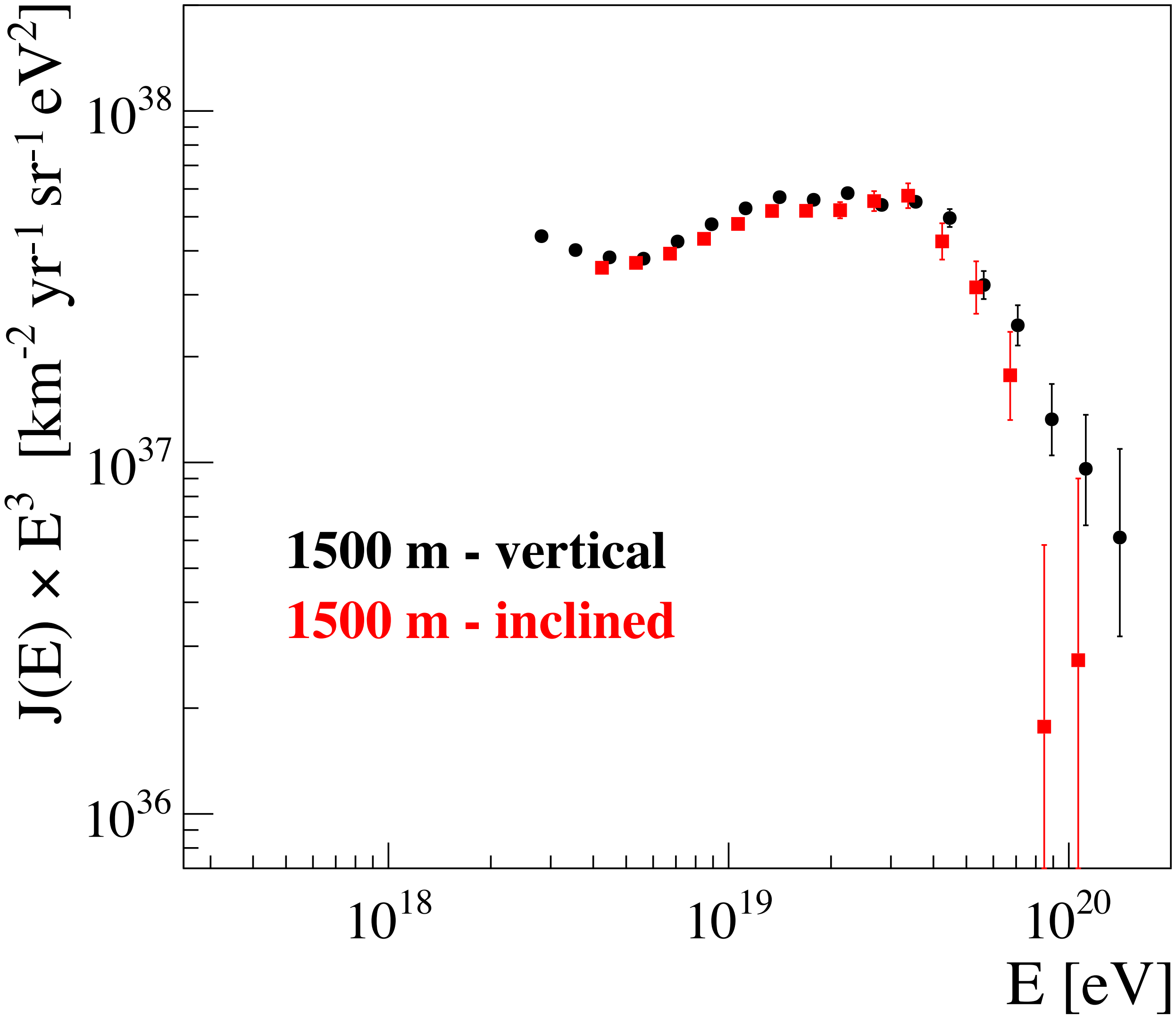
AUGER ENERGY SPECTRA



AUGER ENERGY SPECTRA

1500 m vertical
183332 events E > $10^{18.4}$ eV
51588 km^2 yr sr
$\Delta J/J \sim 5\%$

1500 m inclined
19602 events E > $10^{18.6}$ eV
15122 km^2 yr sr
$\Delta J/J \sim 6\%$

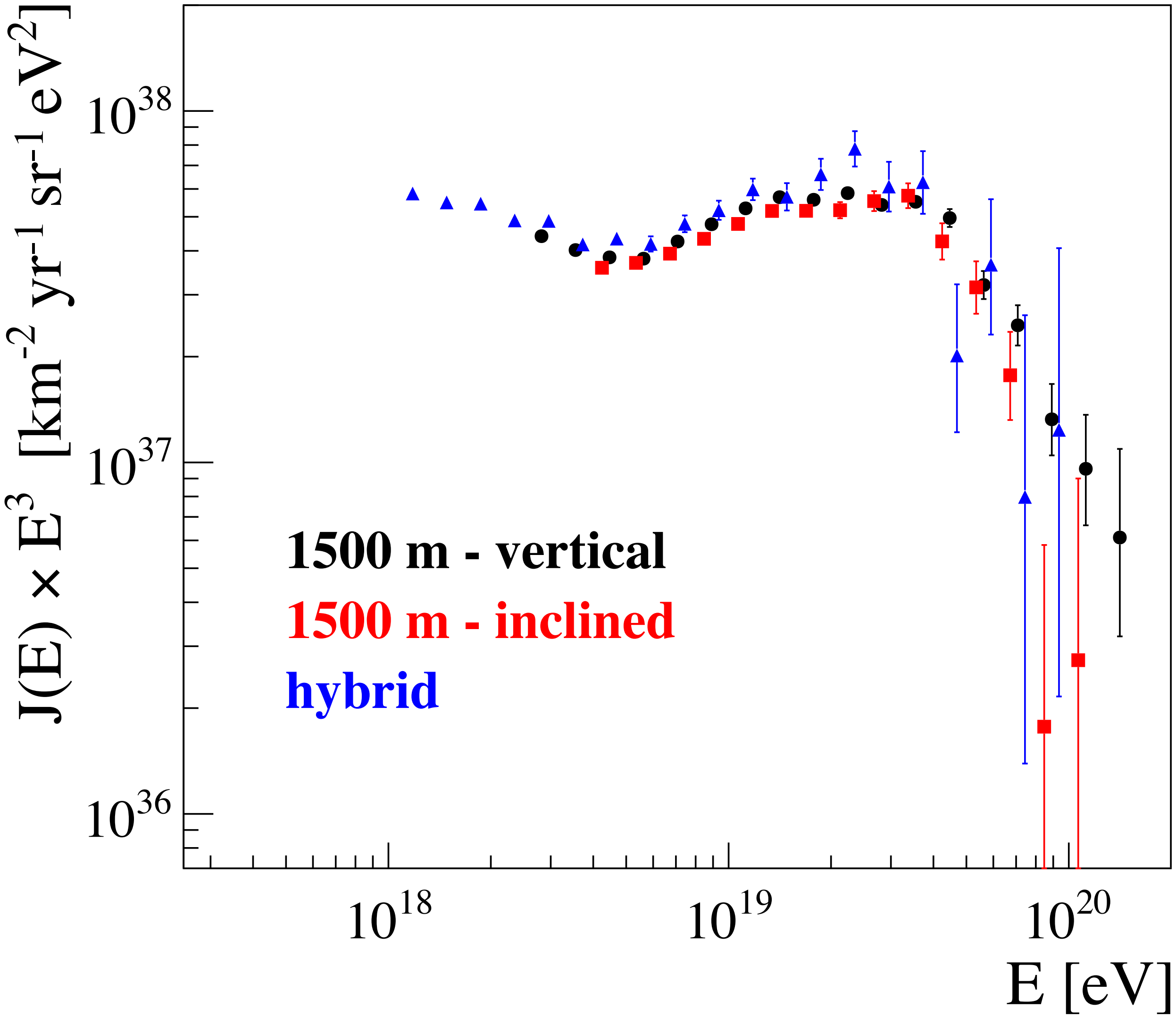


AUGER ENERGY SPECTRA

1500 m vertical
183332 events E > $10^{18.4}$ eV
51588 km^2 yr sr
$\Delta J/J \sim 5\%$

1500 m inclined
19602 events E > $10^{18.6}$ eV
15122 km^2 yr sr
$\Delta J/J \sim 6\%$

hybrid
11680 events E > 10^{18} eV
1946 km^2 yr sr at 10^{19} eV
$\Delta J/J \sim 10\%$



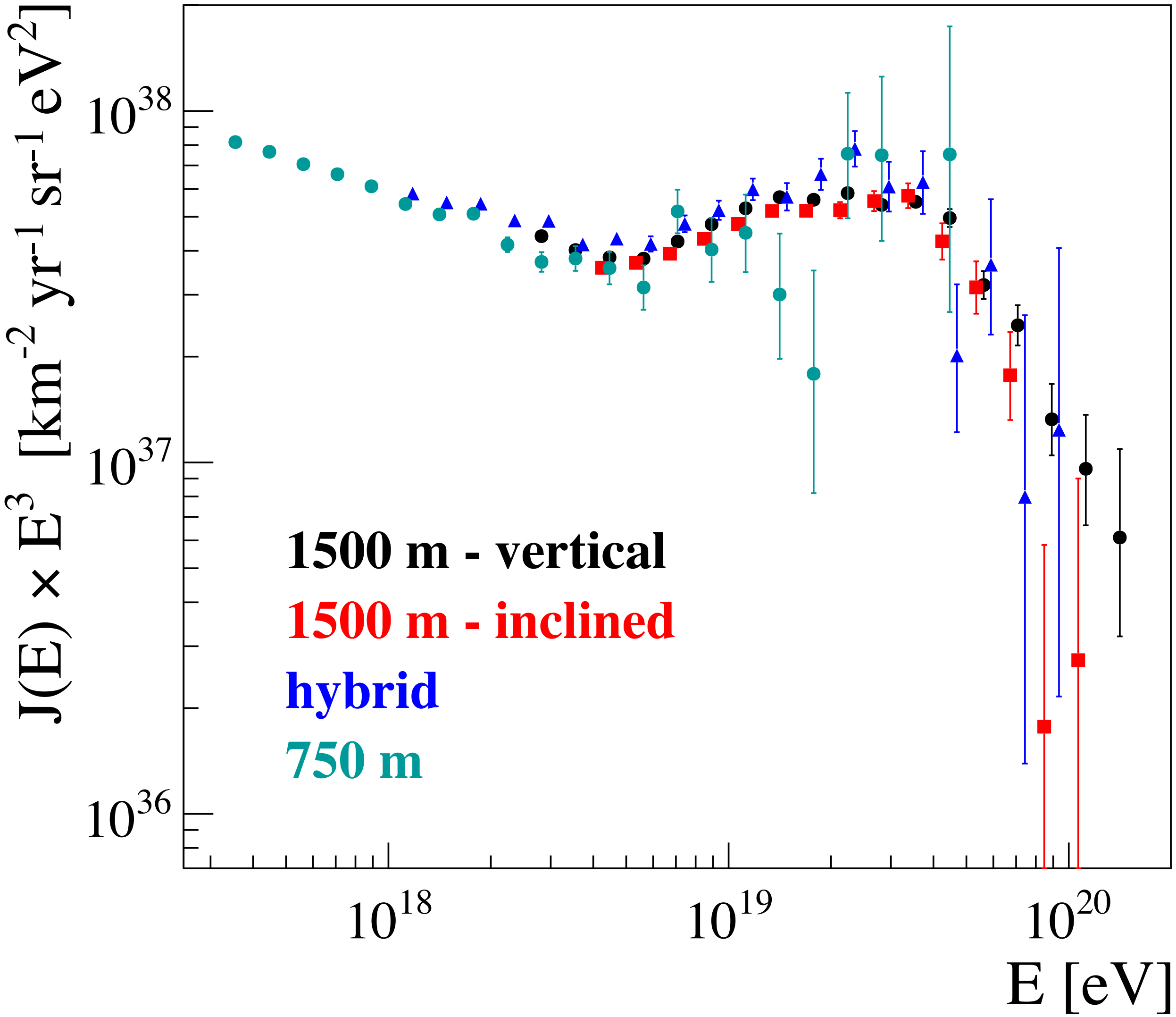
AUGER ENERGY SPECTRA

1500 m vertical
183332 events E > $10^{18.4}$ eV
51588 km^2 yr sr
$\Delta J/J \sim 5\%$

1500 m inclined
19602 events E > $10^{18.6}$ eV
15122 km^2 yr sr
$\Delta J/J \sim 6\%$

hybrid
11680 events E > 10^{18} eV
1946 km^2 yr sr at 10^{19} eV
$\Delta J/J \sim 10\%$

750 m
87402 events E > $10^{17.5}$ eV
228 km^2 yr sr
$\Delta J/J \sim 10\%$



combine the measurements
in the full energy range

AUGER ENERGY SPECTRA

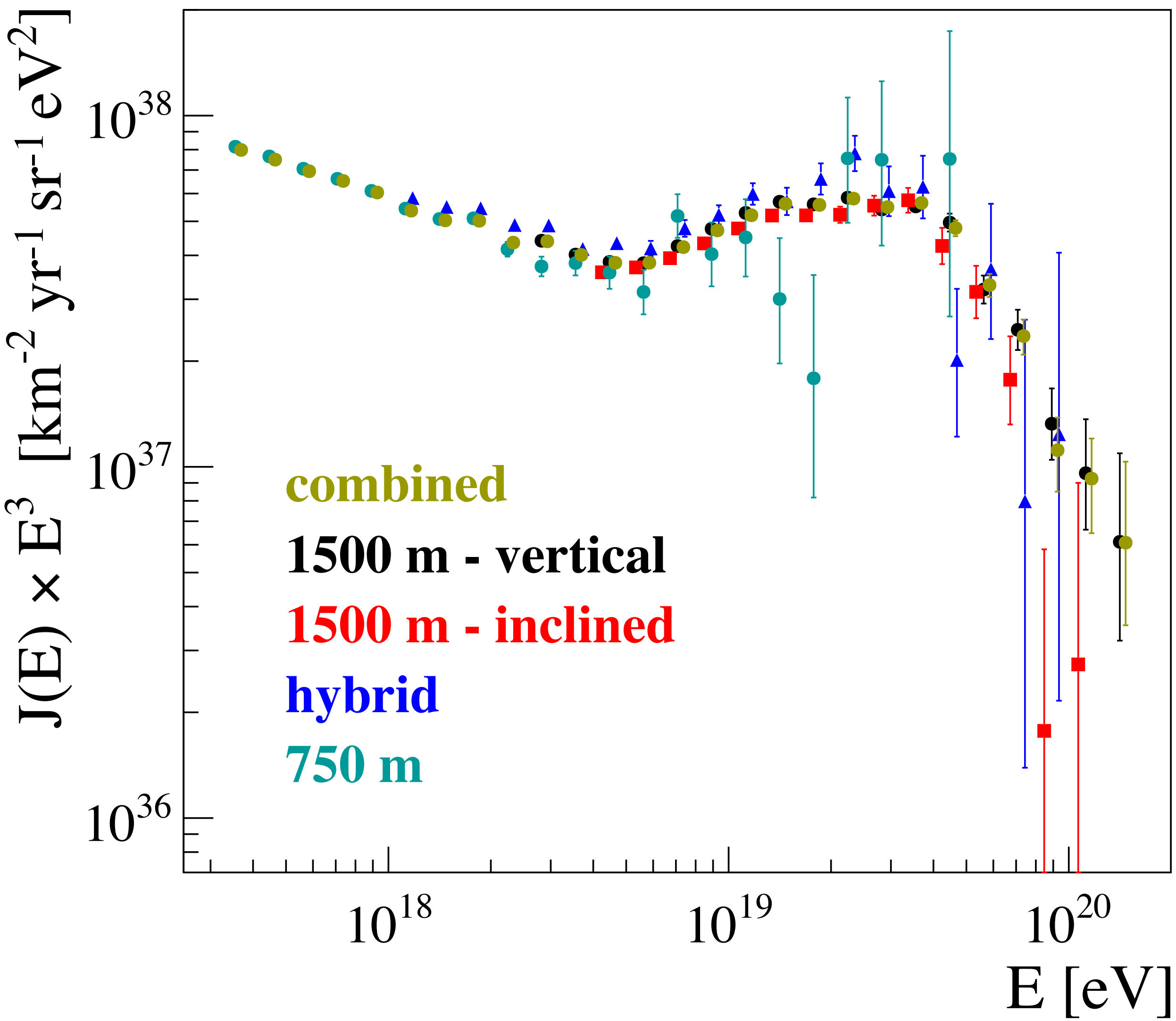
rescaling factors of the fluxes:

1500 m vertical
(-0.8 ± 0.2)%

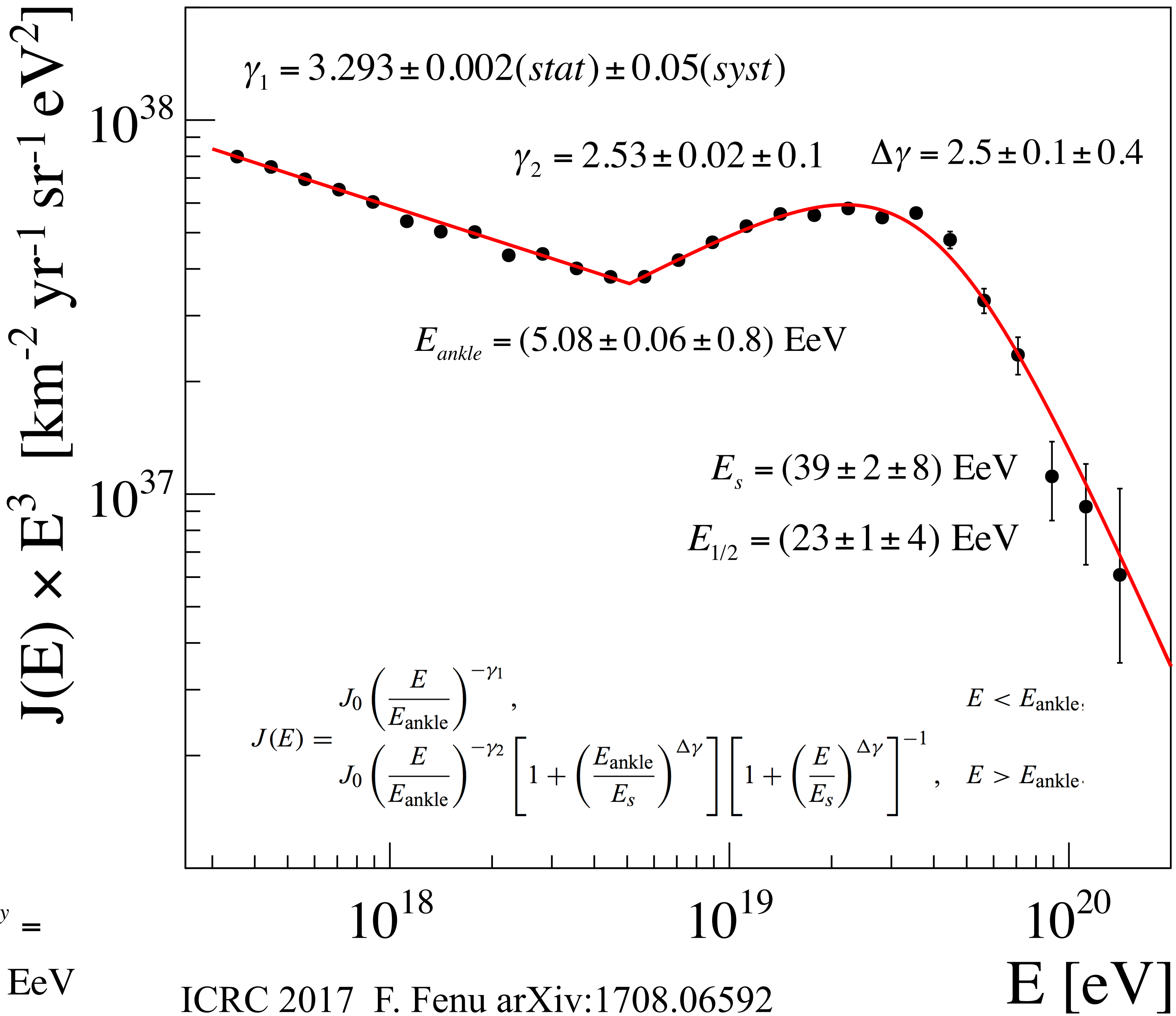
1500 m inclined
(+5.4 ± 0.7)%

hybrid
(-6 ± 2)%

750 m
(-1 ± 4)%



AUGER COMBINED ENERGY SPECTRUM



$E_{1/2}^{Berezinsky} =$ 50 – 60 EeV

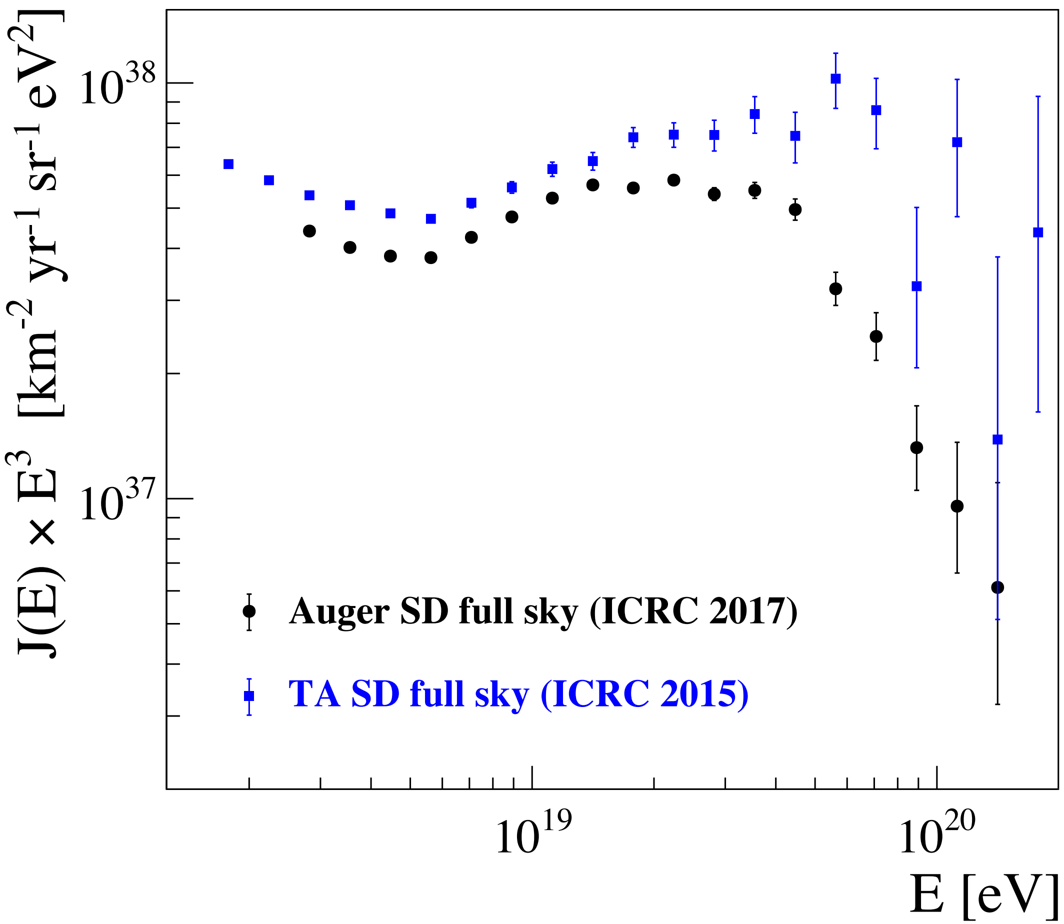
ICRC 2017 F. Fenu arXiv:1708.06592

OUTLOOK

Auger energy spectrum measured with:

- **unprecedented statistics ($67000\ km^2\ sr\ yr$)**
- **~ full data-driven approach**
- **14% uncertainty in the energy scale**

Further results on Auger spectrum:
D. Ivanov - WG talk

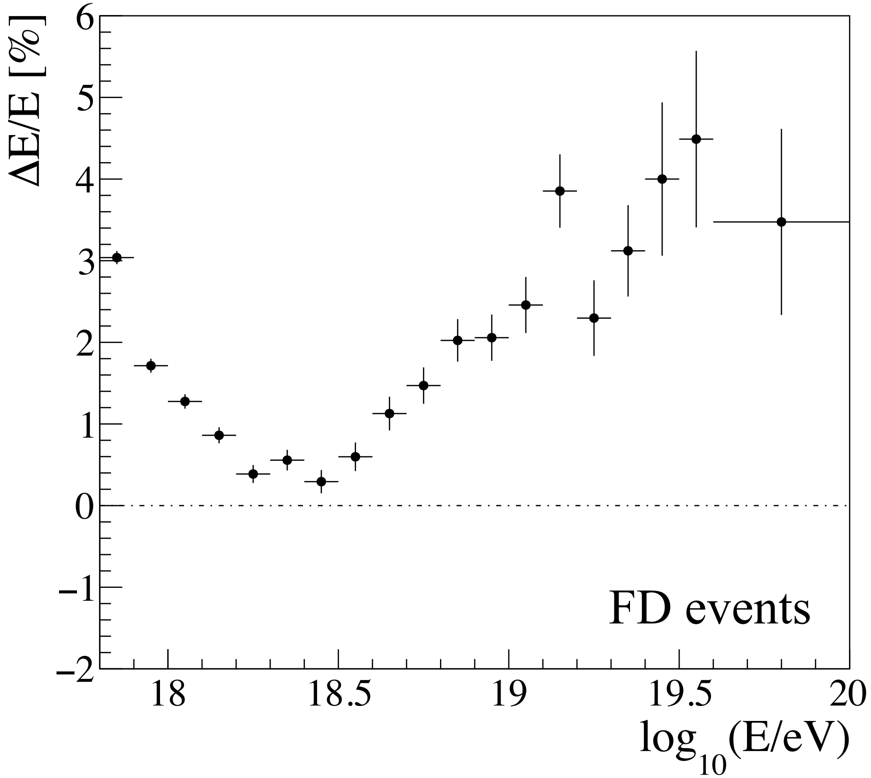


UPDATE OF THE ENERGY SCALE – ICRC 2017

Atmosphere

- aerosol scattering out of the CLF/XLF beam
- multiple scattering of the CLF/XLF beam

→ moderate increase of the aerosol concentration



FD Calibration

- telescope-wise optical efficiency

FD profile reconstruction

- Gaisser-Hillas fit: add a constraint in $\frac{E_{cal}}{dE/dX_{\max}}$

Invisible energy from inclined showers

note: some of the systematic uncertainties needs to be update