Measurement of the energy spectrum of ultra-high energy cosmic rays using the Pierre Auger Observatory

Valerio Verzi[1] for the Pierre Auger Observatory[2]

[1] *INFN, Sezione di Roma "Tor Vergata", via della Ricerca Scientifica 1, 00133 Roma, Italia*

[2] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*

Full author list: http://www.auger.org/archive/authors_icrc_2019.html

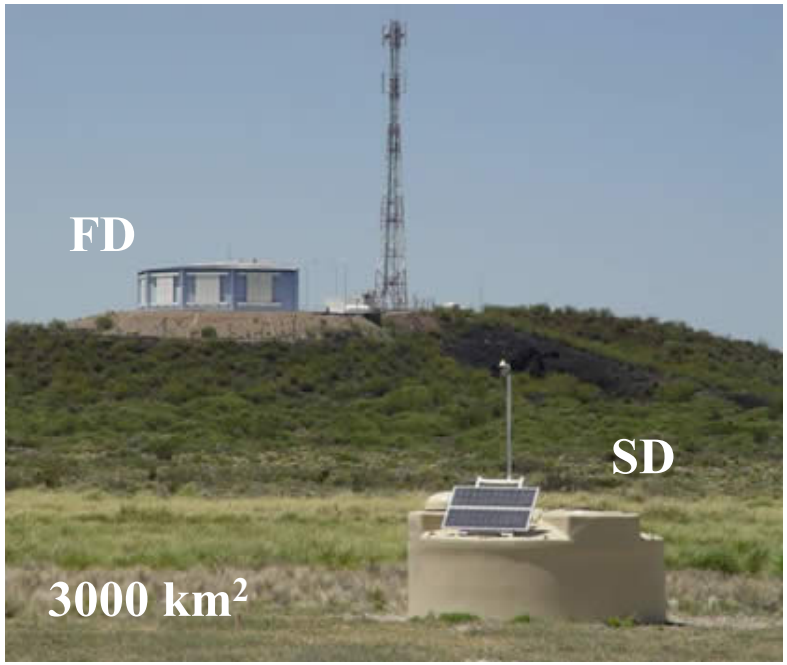
INFN Istituto Nazionale di Fisica Nucleare

PIERRE AUGER OBSERVATORY

Hybrid Observatory

Surface Detector array (SD)
1661 water-Cherenkov detectors on 1500 m and 750 m triangular grid
(+) duty cycle ~ 100%
(-) shower size at ground ∝ E (systematics)

Fluorescence Detector (FD)
27 telescopes in 4 sites
(-) duty cycle ~ 15%
(+) calorimetric measurement of E



A. Castellina highlight
B. Dawson #231 A. Coleman #225

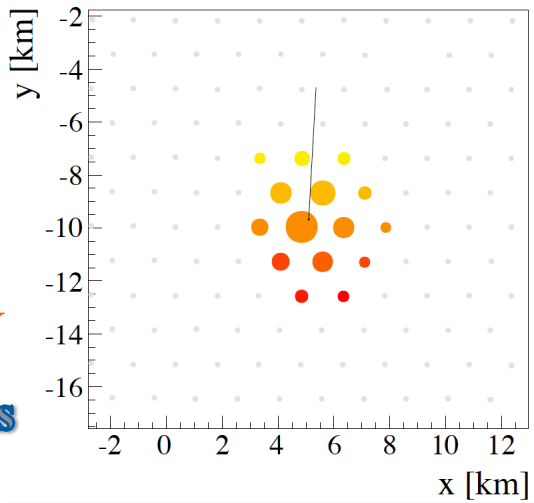
- energy scale of the Observatory set by the FD with a 14% systematic uncertainty
- precise measurement of the flux up to 10^{20} eV

energy spectrum over 4 decades in energy

SD
1500 m
$\theta < 60^0$

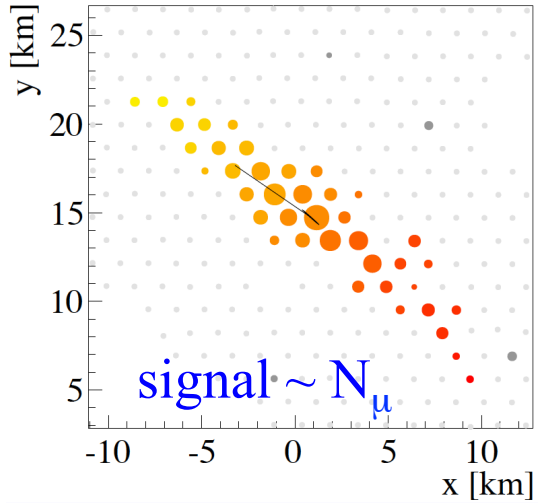
$E > 10^{18.4}$ eV

improved analysis



SD
1500 m
$60^0 < \theta < 80^0$

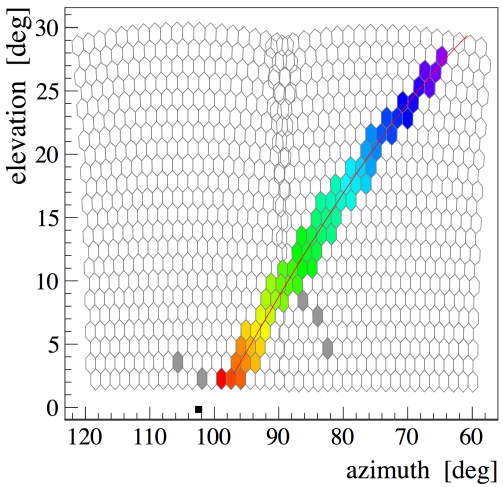
$E > 10^{18.6}$ eV



FD + SD stat.
hybrid

(15% duty cycle)

$E > 10^{18}$ eV



SD **new**
750 m
$\theta < 40^0$

A. Coleman #225

$E > 10^{17}$ eV

FD-HEAT **new**
Cherenkov

V. Novotny #374

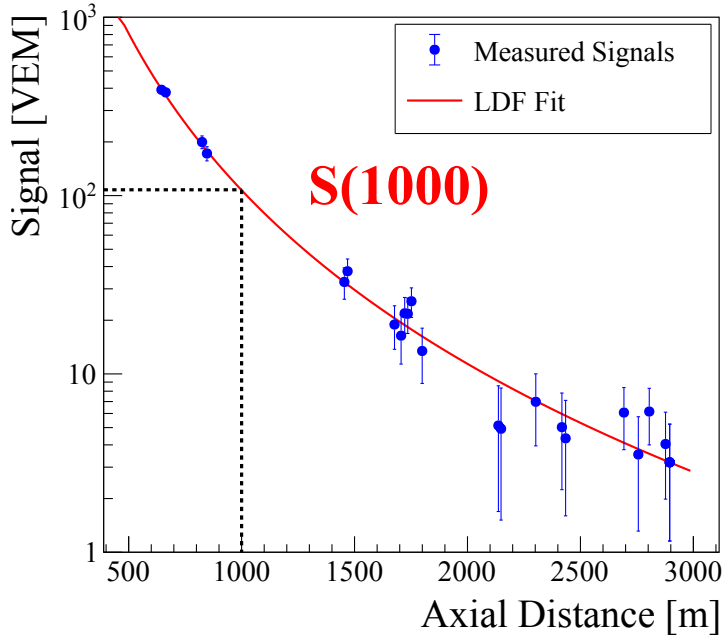
$E > 10^{16.5}$ eV

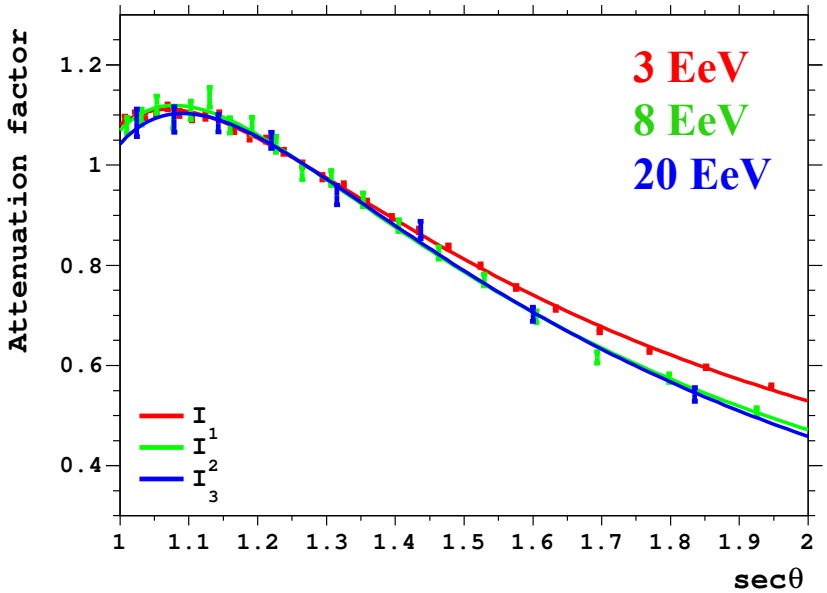
energy estimation for 1500 m array θ < 60^0 events

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

D. Mockler #353

use the CIC method to remove the zenith angle dependence of S(1000). CIC at different intensity thresholds new





S_{38}

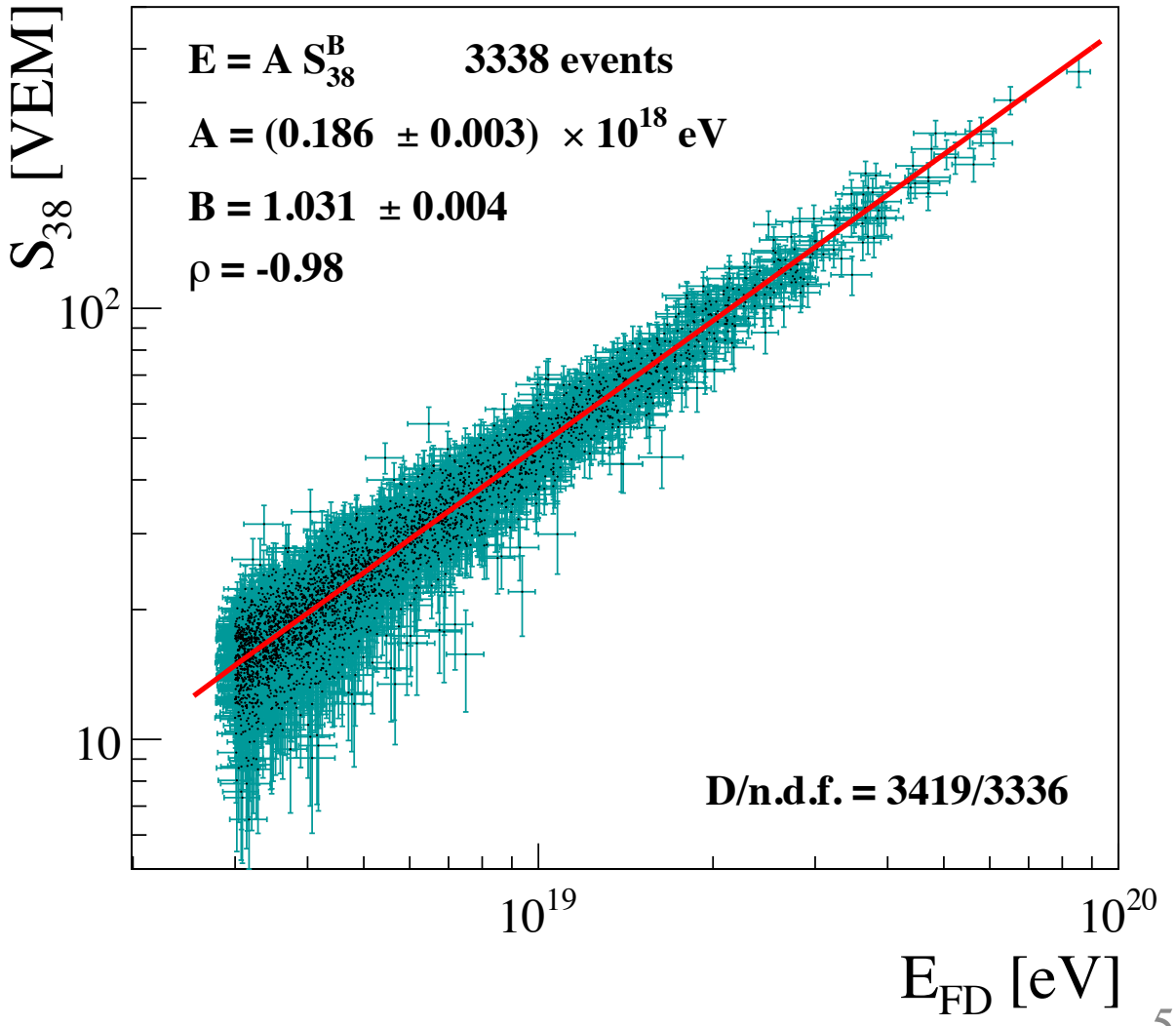
note: correction determined from data (no use of simulations)

energy estimation for 1500 m array $\theta < 60^0$ events

high-quality events triggered independently by SD and FD

correlation well described by a power-law relationship

maximum-likelihood fit using a "bootstrap" estimate of the p.d.f. and event-by-event uncertainties



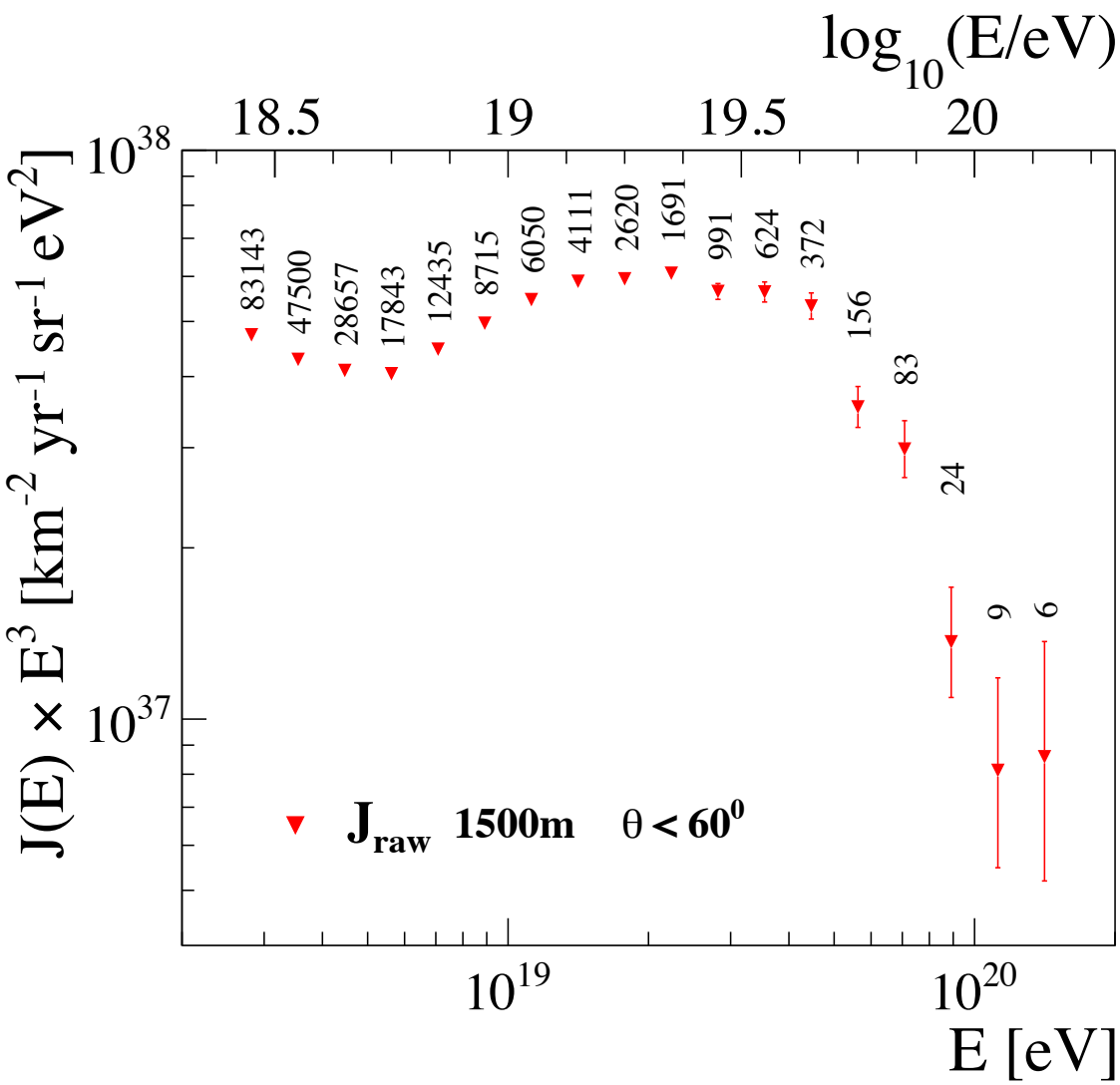
raw energy spectrum using 1500 m array $\theta < 60^0$ events

$$J = f_{res} J_{raw} = f_{res} \frac{N}{\varepsilon \, \Delta E}$$

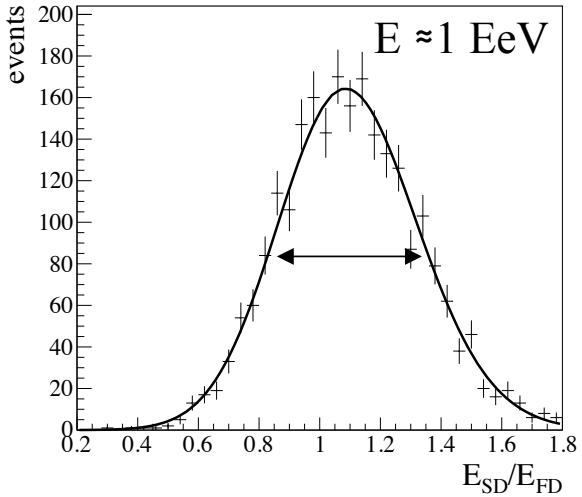
measurements done with full trigger efficiency

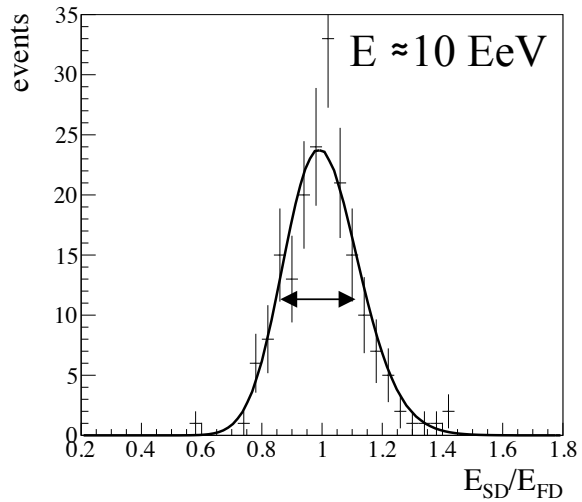
$\varepsilon = (60400 \pm 1800)$ km^{2}sr yr

215030 events
with E > $10^{18.4}$ eV

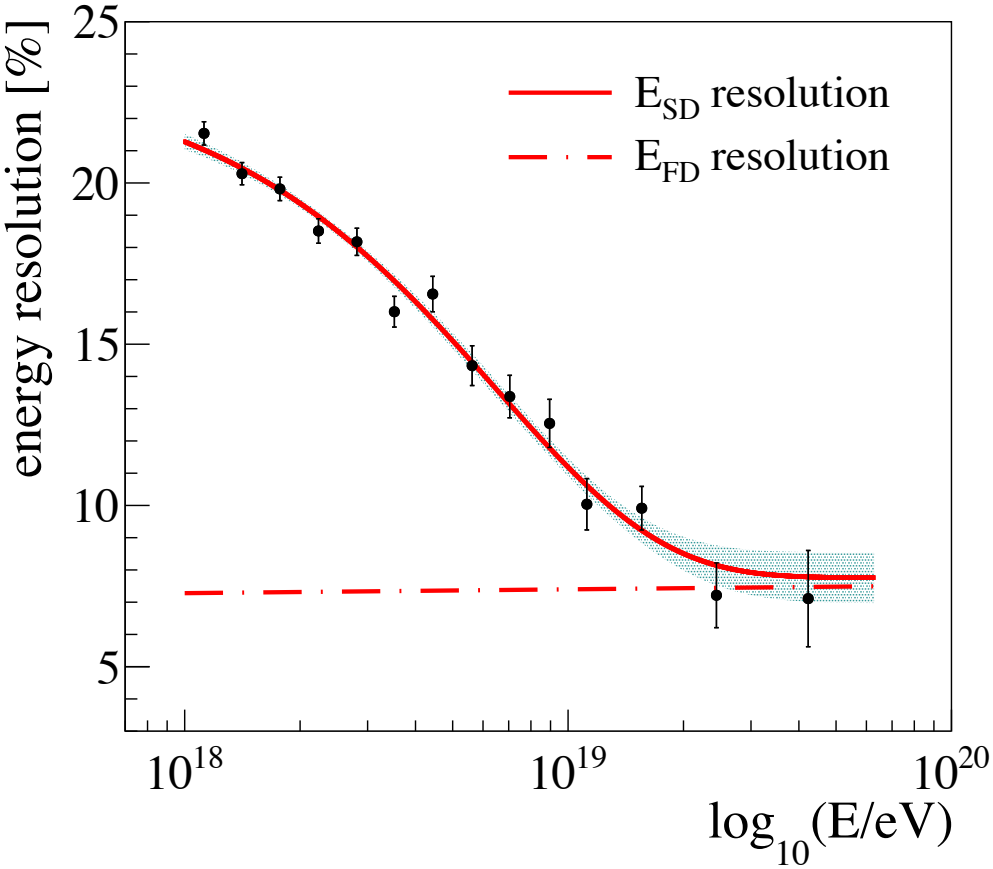


ingredients to calculate f_{res} from hybrid data new





E_{SD} resolution knowing the E_{FD} one

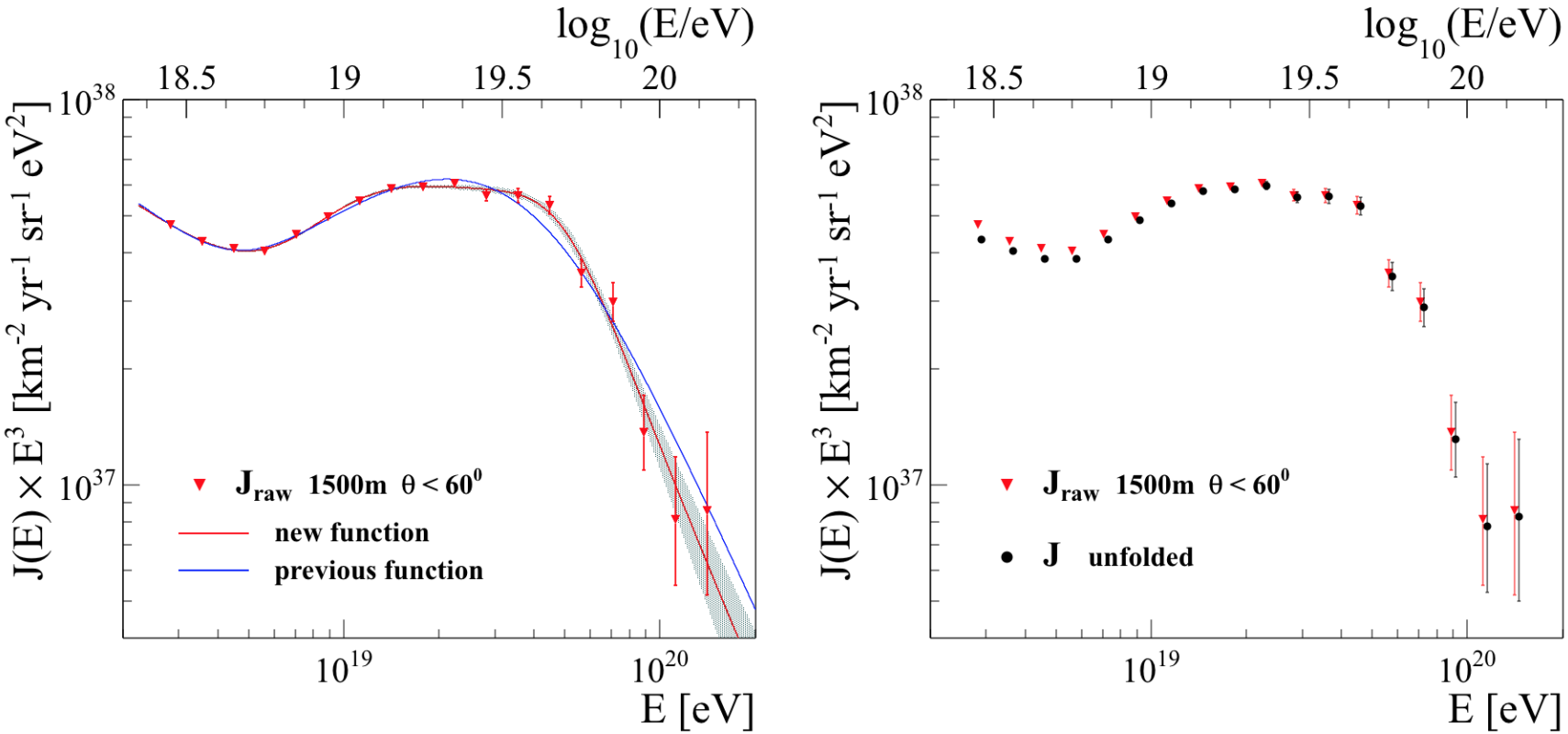


also E_{SD} bias and trigger efficiency at lower energies

unfolded spectrum

f_{res} calculated using a forward-folding technique

- new function: sequence of 4 power-laws with 3 inflection points **new**
- previous function: slow transition between ankle and suppression
- f_{res} small at all energies



previous function discarded with a significance of 3.2σ

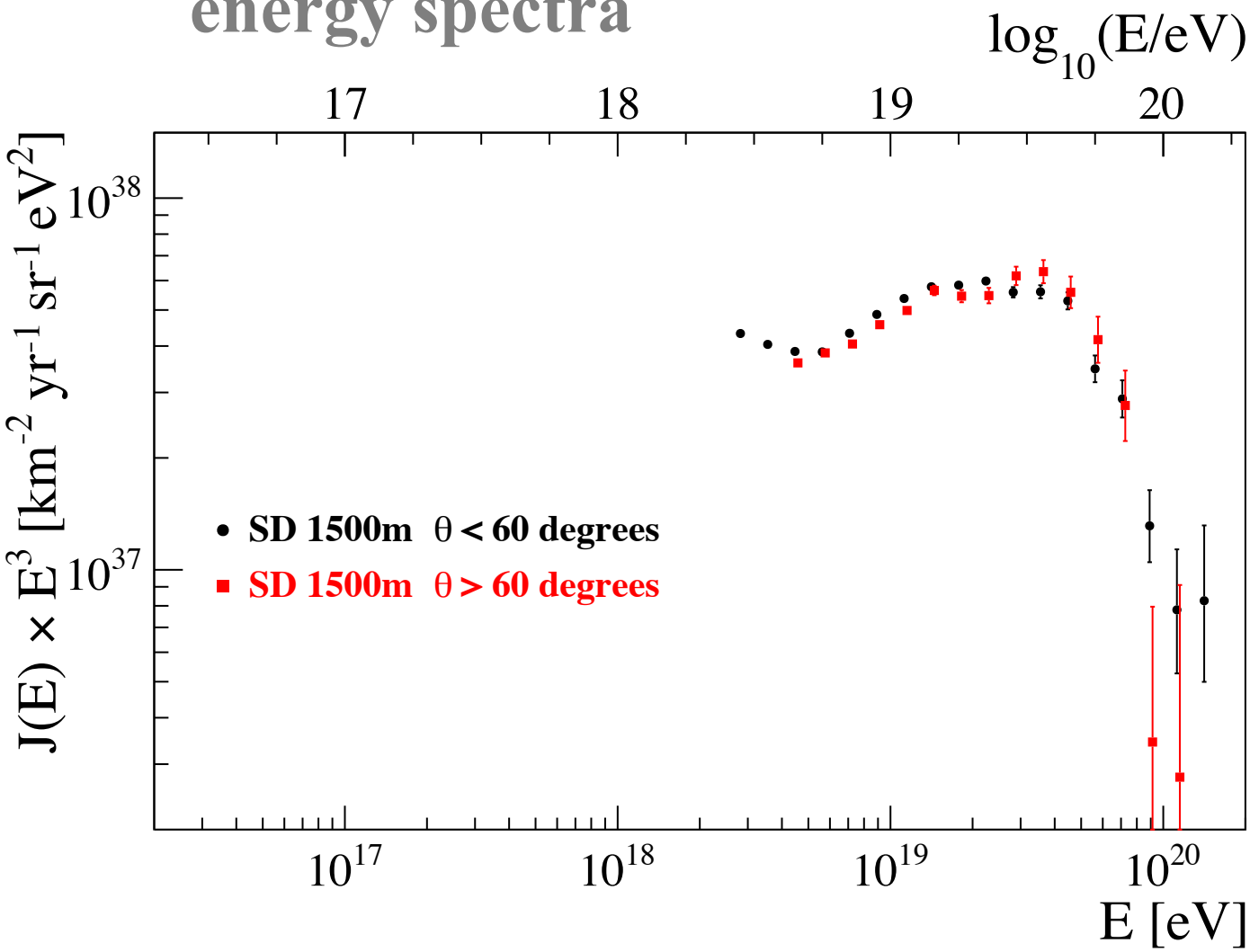
energy spectra

full trigger efficiency exposure (30% more) 17447 km^2 sr yr

above $10^{18.6}$ eV 24209 events

similar data-driven approach but completely different reconstruction technique

energy resolution 22% - 10%



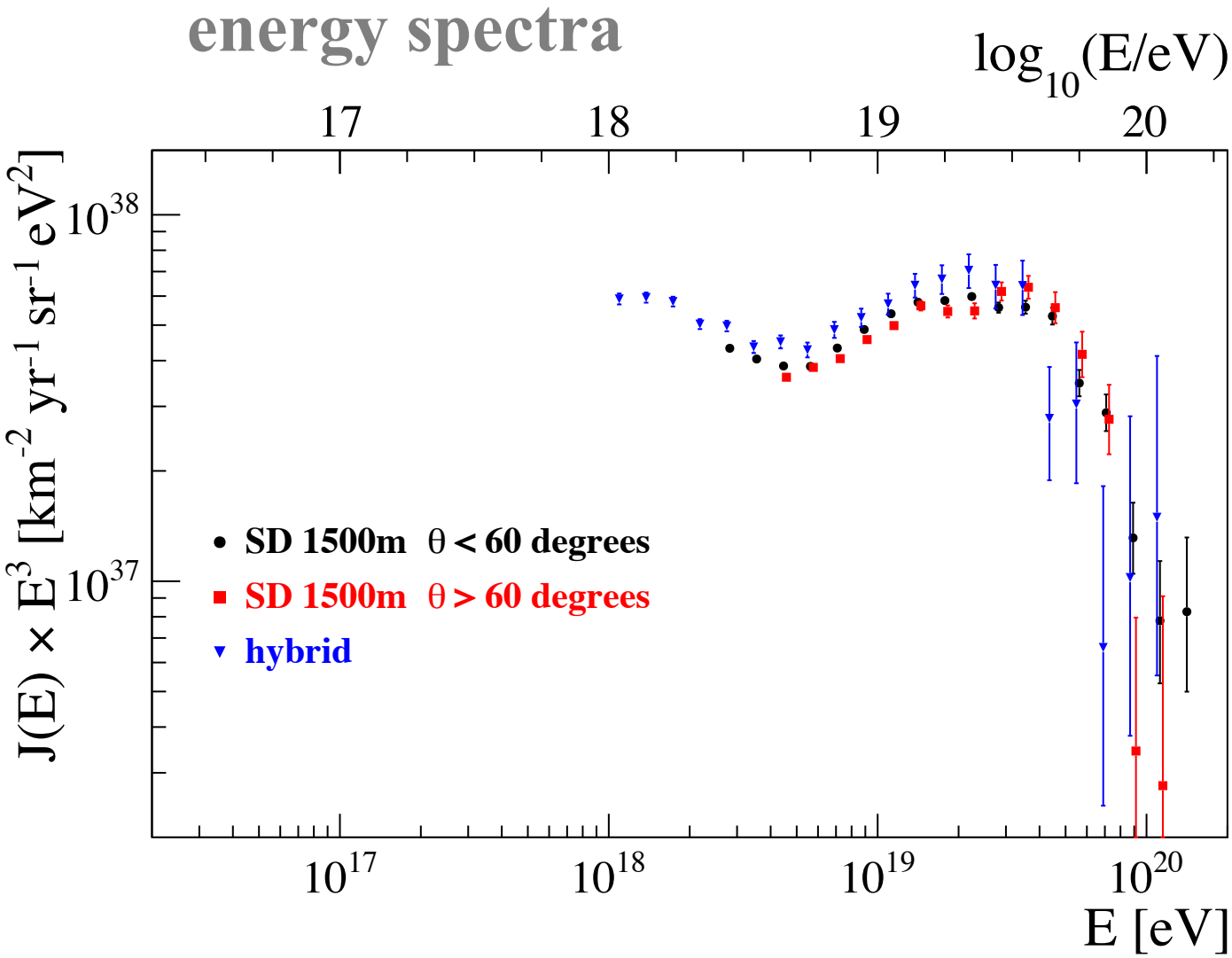
energy spectra

13655 events above 10^{18} eV

full time-dependent simulation of FD events

exposure [km^2 sr yr]
1 EeV 265 km^2 sr yr
10 EeV 2248 km^2 sr yr

energy resolution ≈ 7.4%



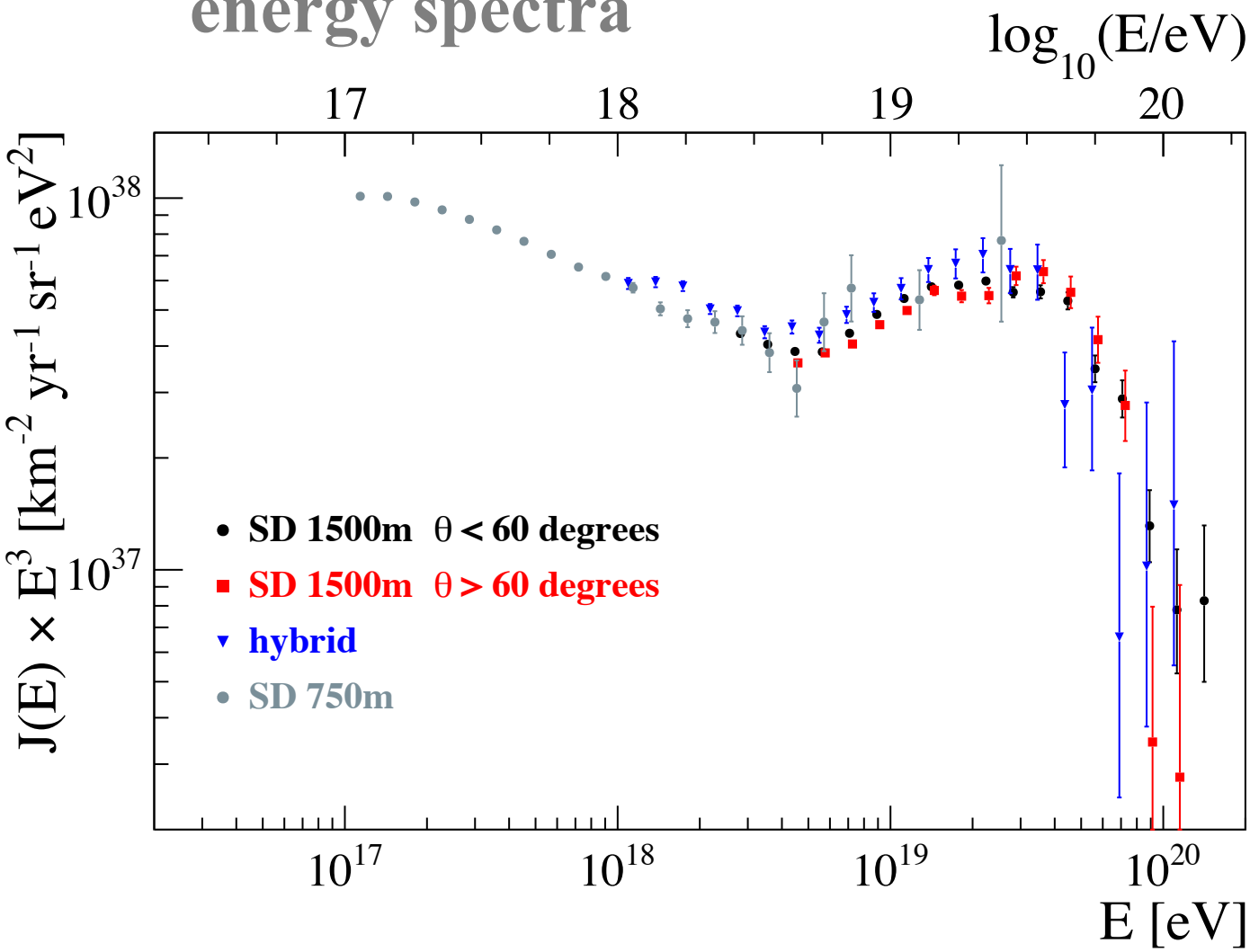
energy spectra

A. Coleman #225

full trigger efficiency exposure
105 km^2 sr yr

569285 events above 10^{17} eV

data-driven approach similar to the ones of the 1500m array



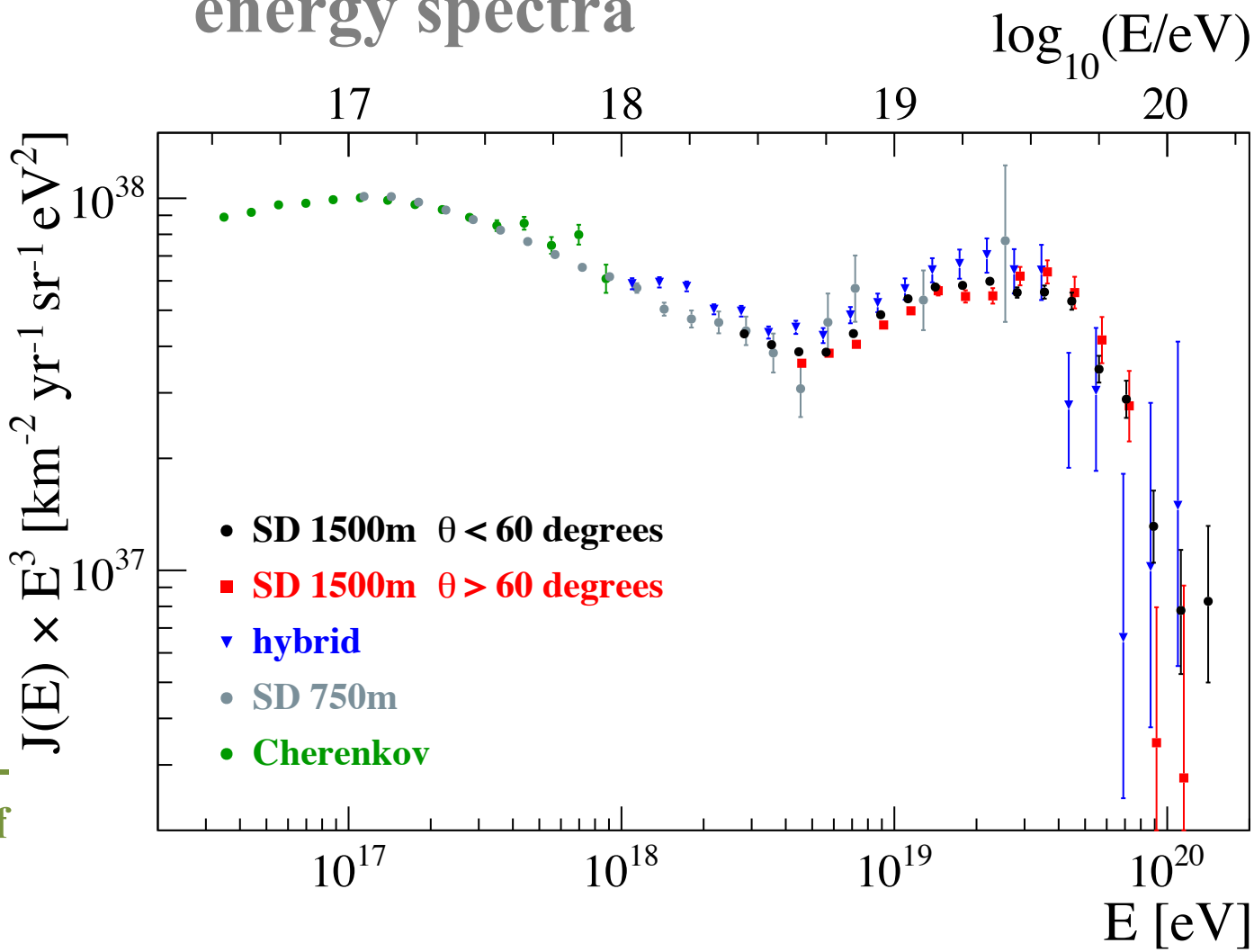
energy spectra

V. Novotny #374

69793 events above $10^{16.5}$ eV

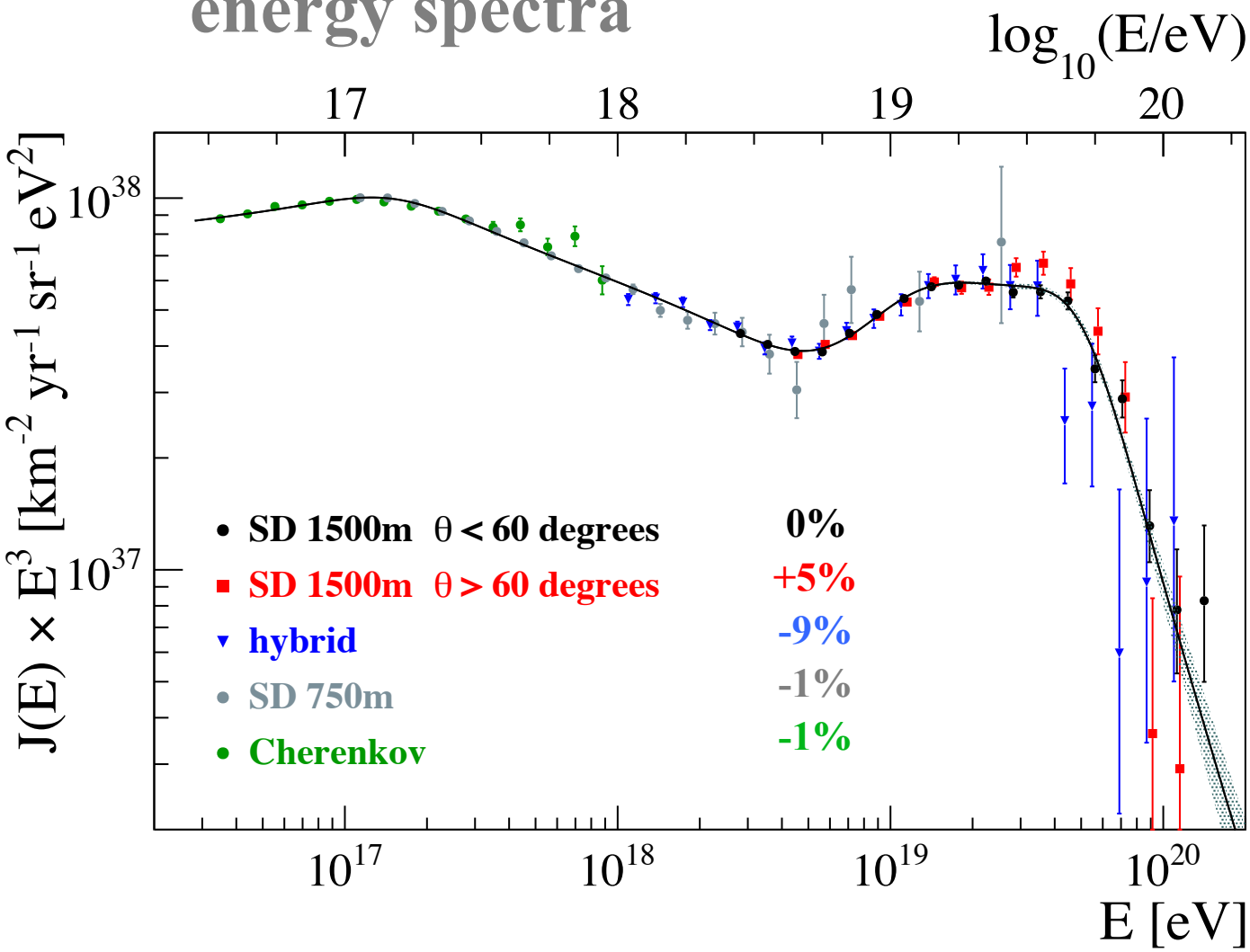
energy deposited from a profile constrained geometry fit and invisible energy correction inferred from muon data

exposure from full time-dependent simulation of FD events

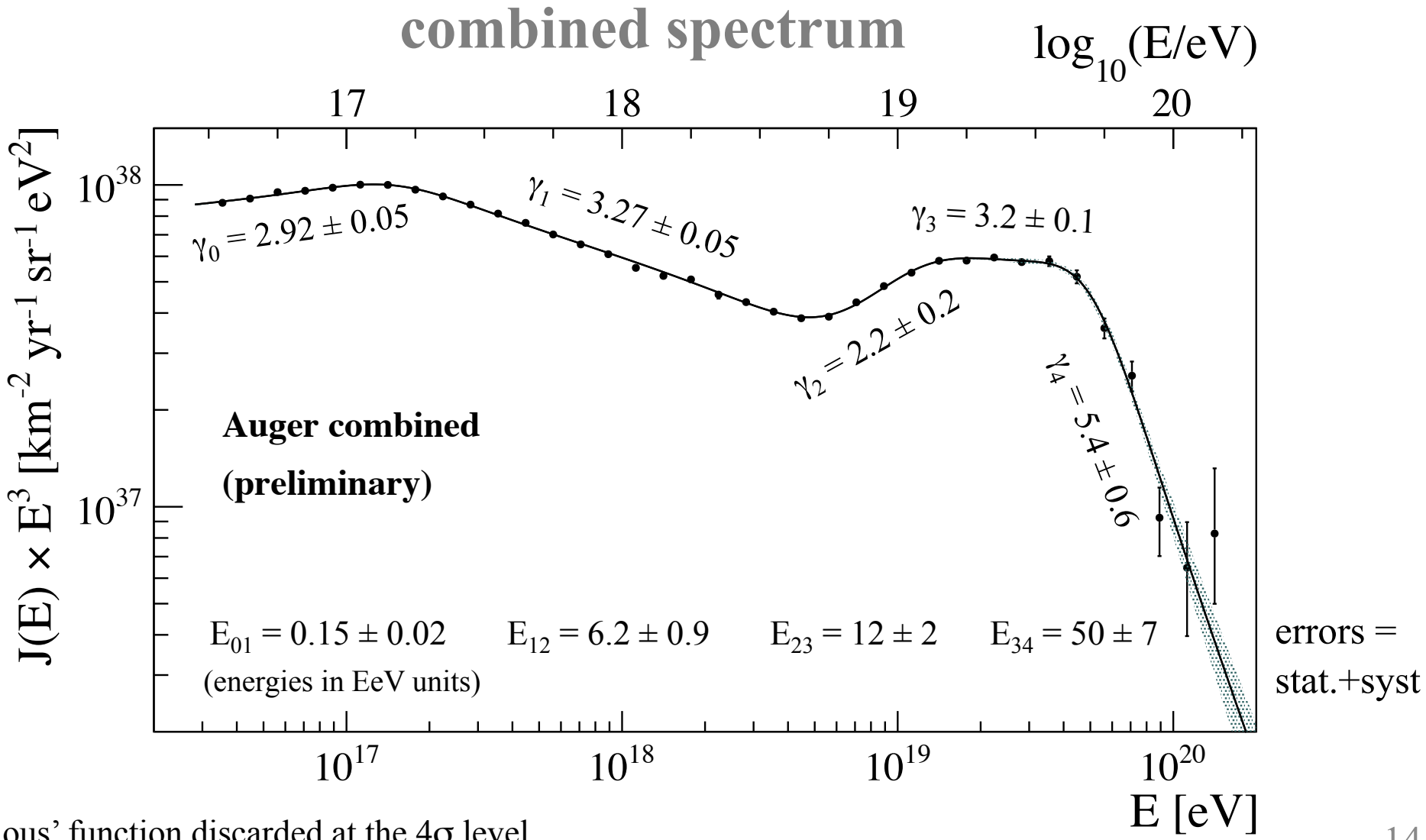


energy spectra

fluxes in good agreement among them once rescaled by normalization factors that are consistent with the systematic uncertainties



combined spectrum



errors = stat.+syst

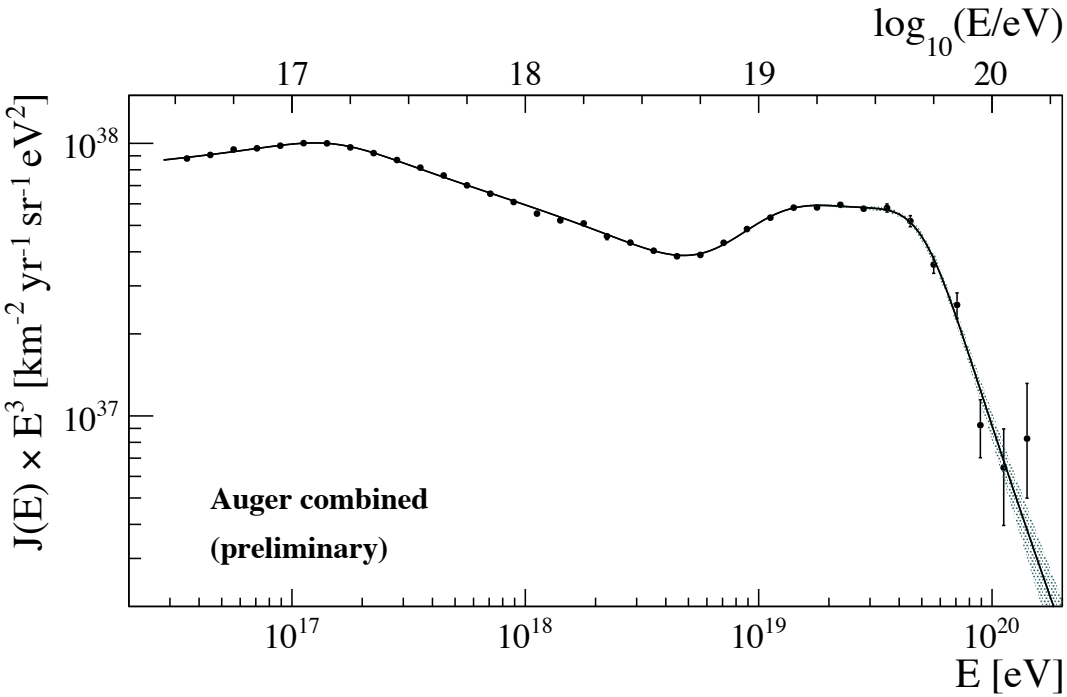
'previous' function discarded at the 4σ level

OUTLOOK

- **improved 1500 m array $\theta < 60^0$ spectrum (no use of simulations)**
- **independent measurements with 1500 m array $\theta > 60^0$ and hybrid events**
- **lower the threshold down to $10^{16.5}$ eV with the 750 m and Cherenkov events**

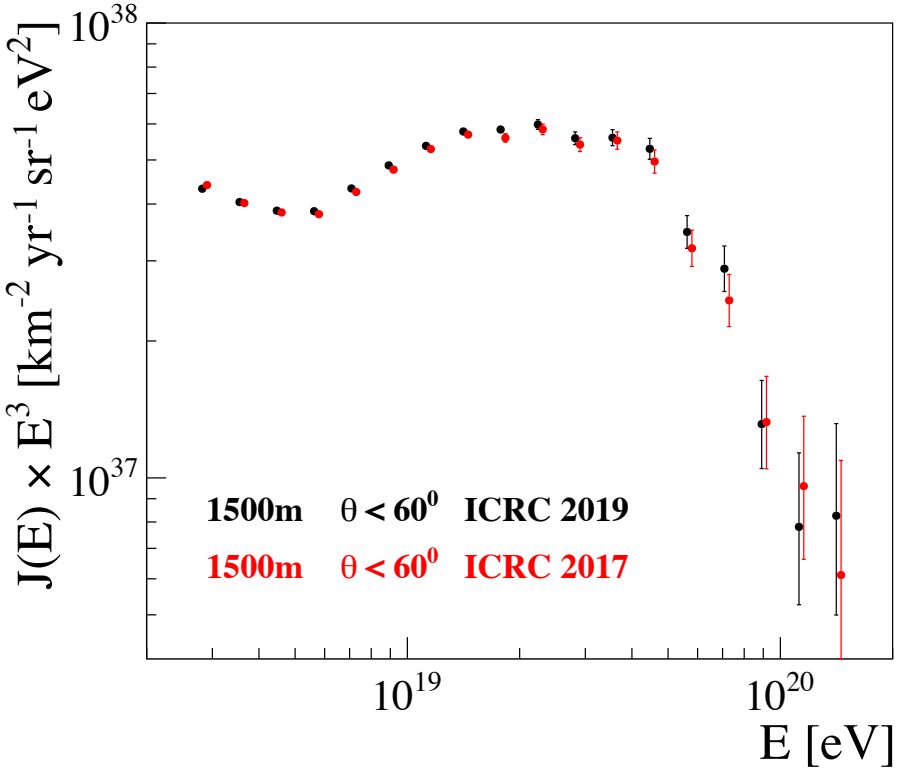
➢ **combined spectrum with a common energy scale:**

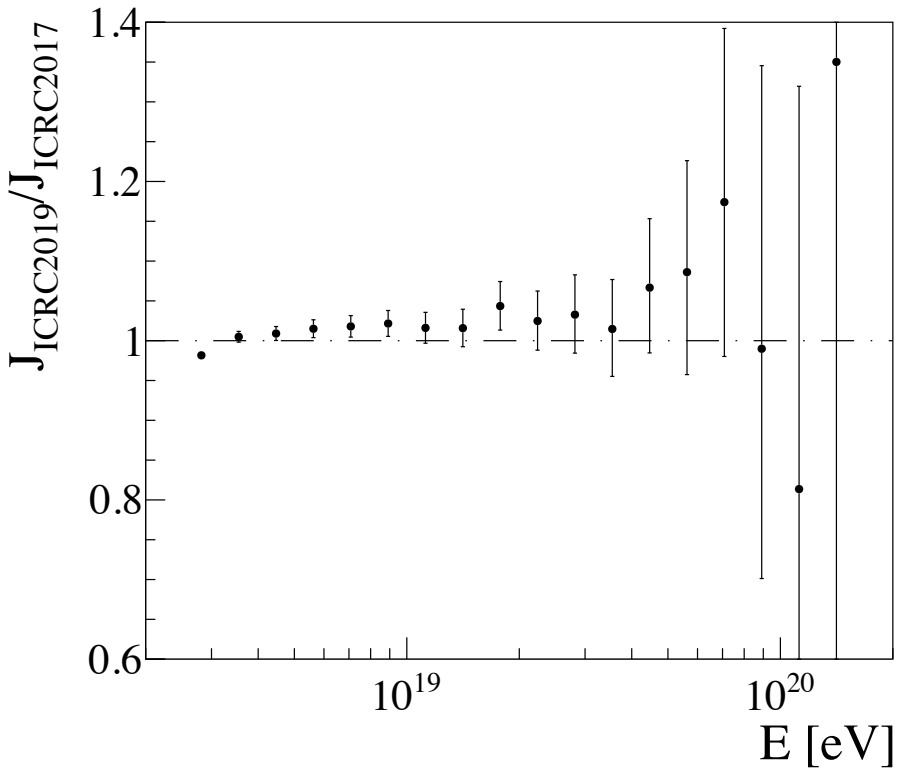
- ***second knee* and *ankle***
- **an indication of a further inflection point at E ~ 10 EeV**
- **abrupt suppression at the highest energies**



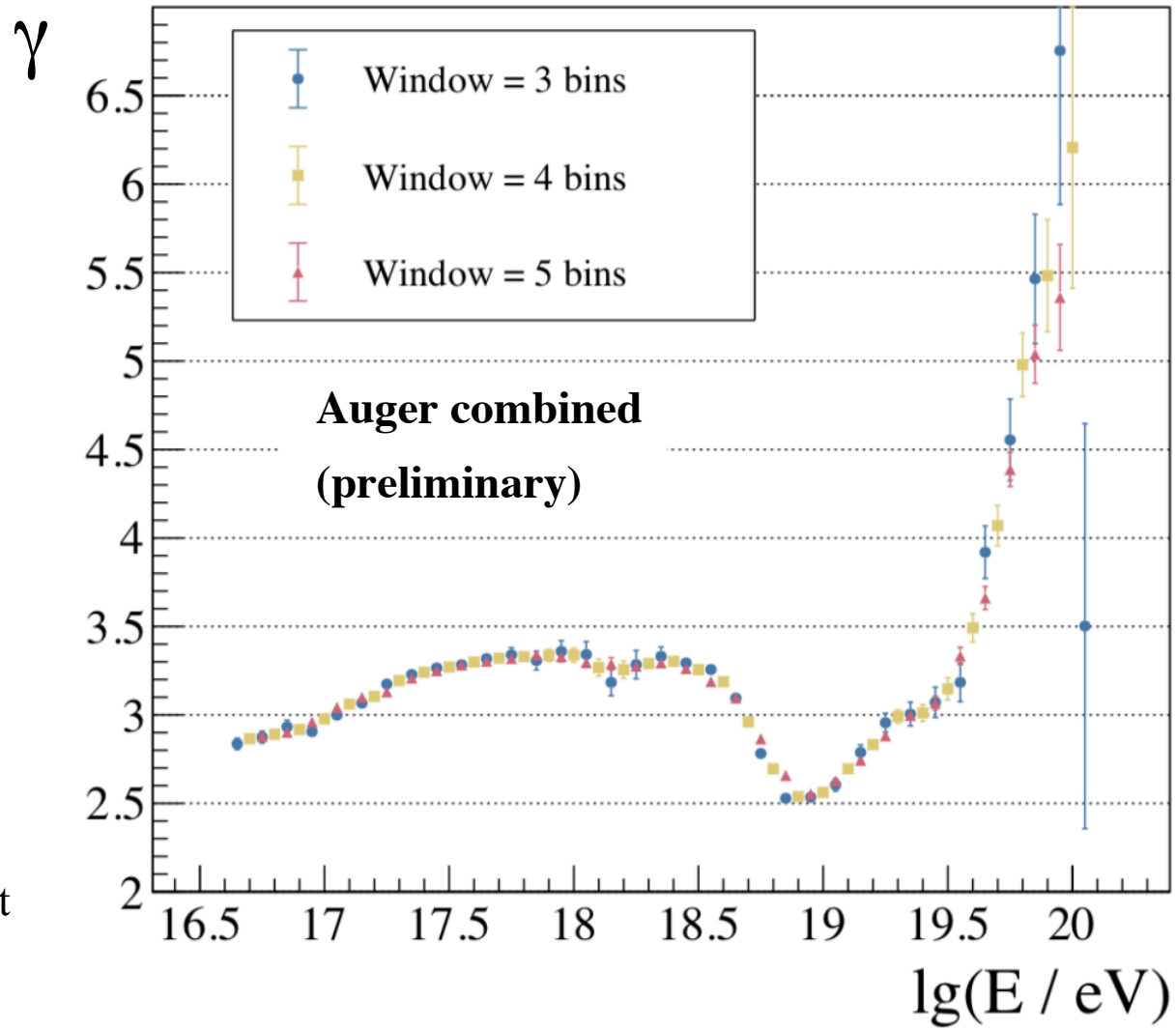
THANKS

1500 m array θ < 60⁰ spectrum: ICRC2019 vs ICRC2017





$$J \sim E^{-\gamma}$$



A. Castellina highlight