# Energy spectrum of cosmic rays measured using the Pierre Auger Observatory

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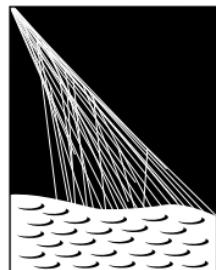
The Pierre Auger Observatory
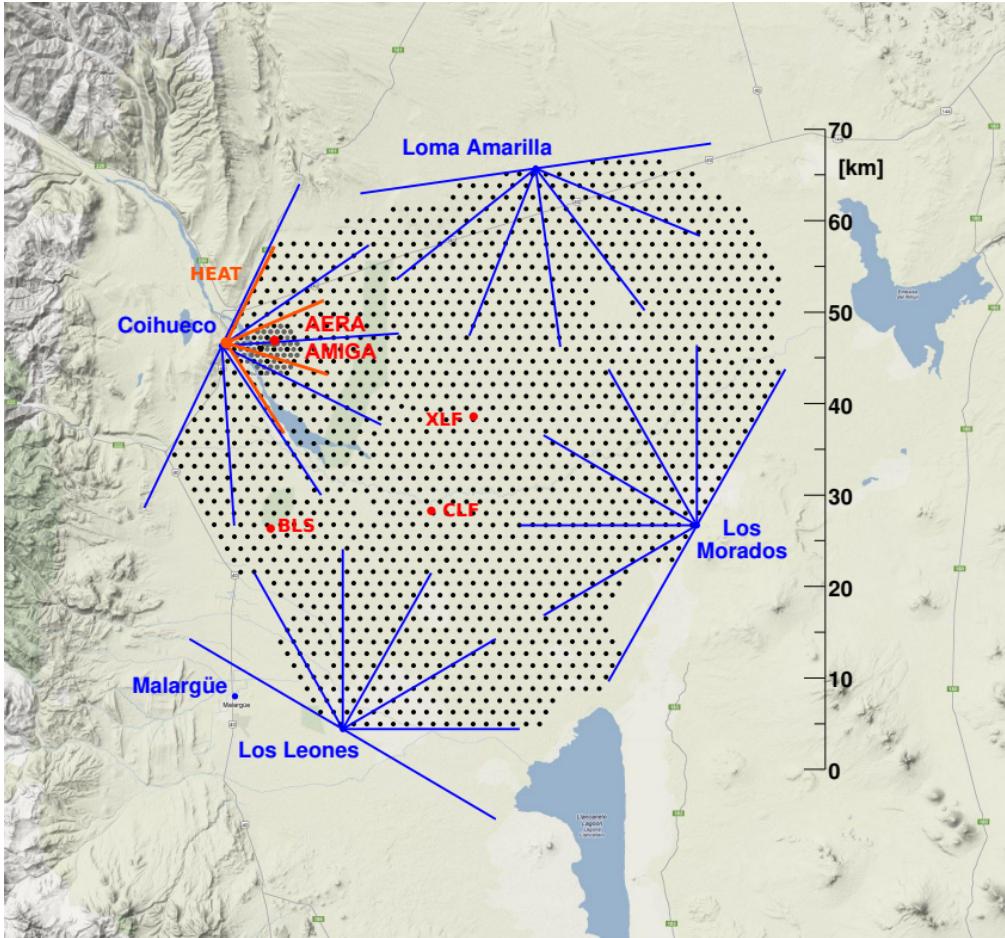
Surface detector (SD)

- 1600 water-Cherenkov stations
- triangular grid array
  - **spacing of 1500 m**
    - 1500 m vertical reconstruction (zenith θ < 60°)
    - 1500 m inclined reconstruction (60° < θ < 80°)
  - **spacing of 750 m**
    - 750 m vertical reconstruction (θ < 40°)

Fluorescence detector (FD)

- 4 sites with 27 telescopes
  - 24 horizontally-looking
  - 3 High Elevation Auger Telescopes (HEAT)
- hybrid data - FD+SD
- Cherenkov-dominated events - FD only

Hybrid detection of extensive air showers

FD
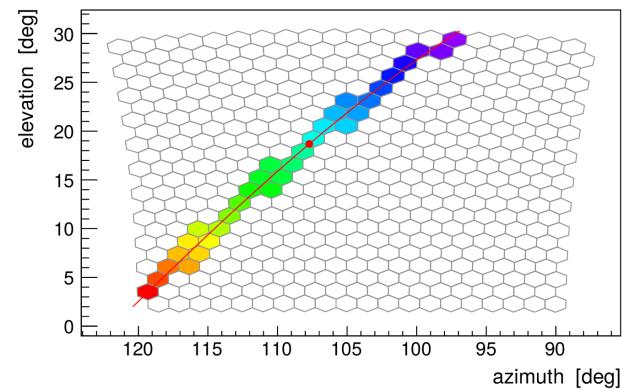
**SD**
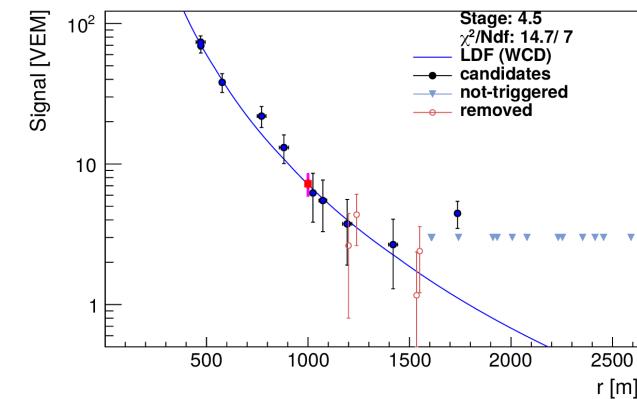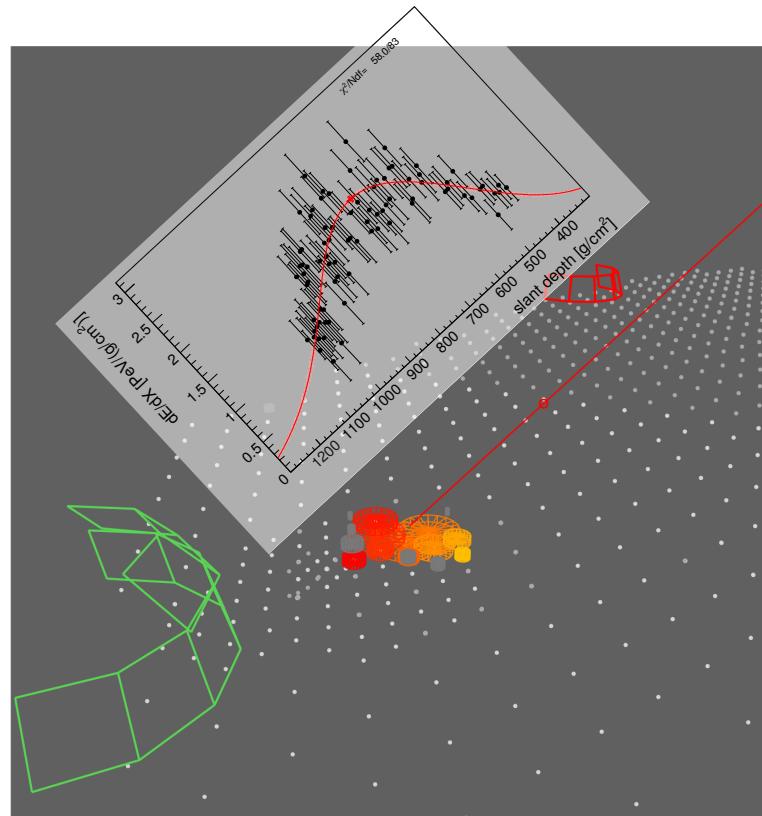
Hybrid detection of extensive air showers

FD **E$_{FD}$** **SD**

S(1000)

4
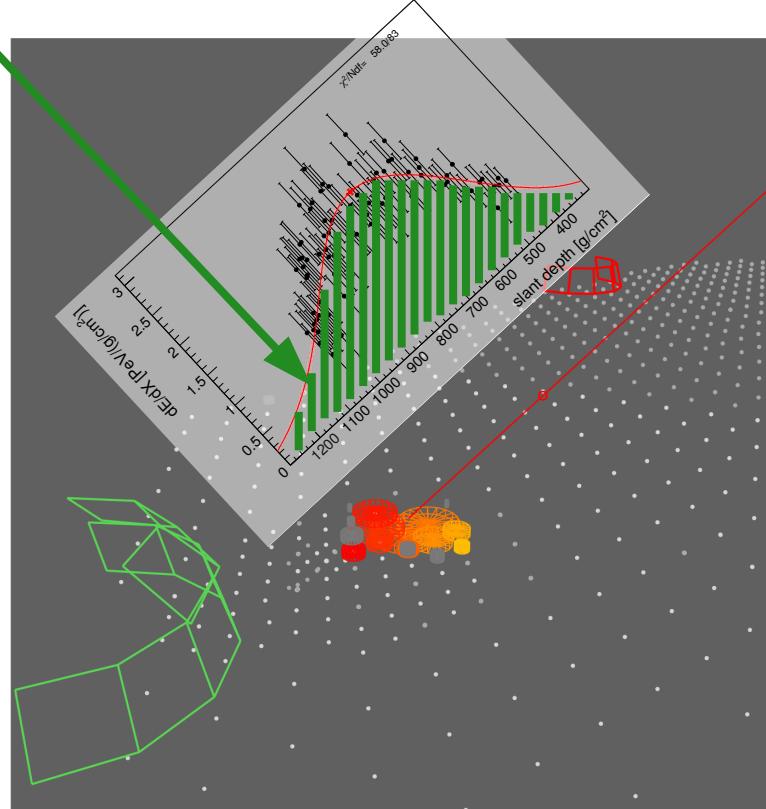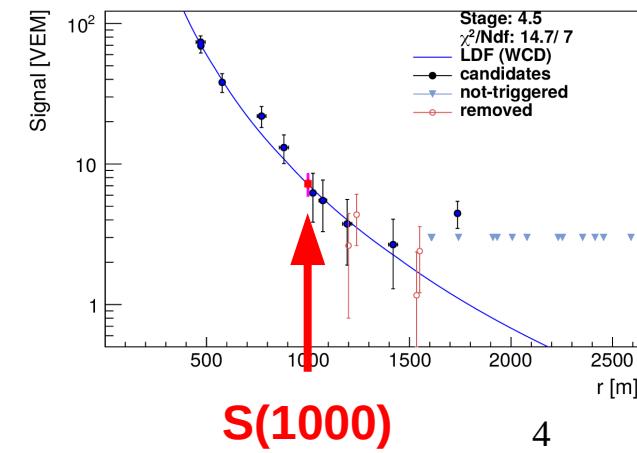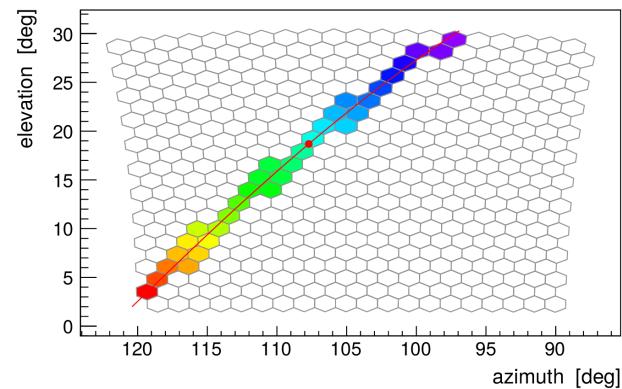
SD events

SD 1500 m vertical
θ < 60°
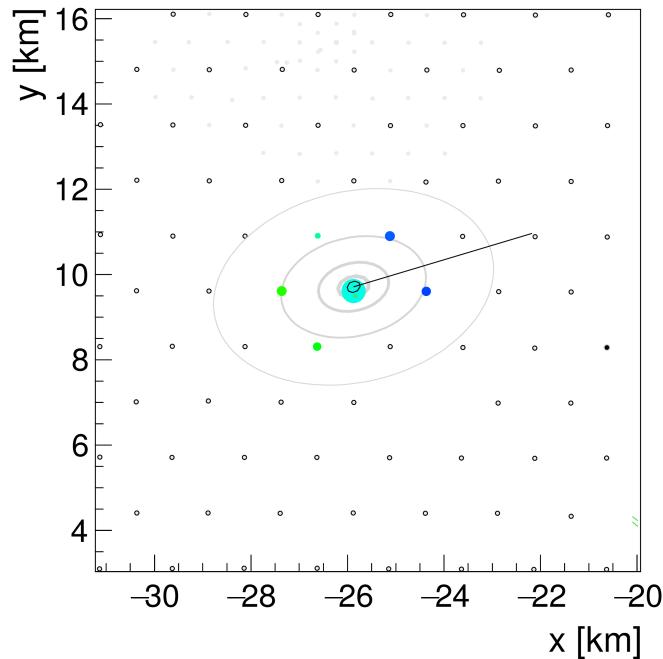
S(1000) – shower size

## SD 1500 m inclined
### 60° < θ < 80°
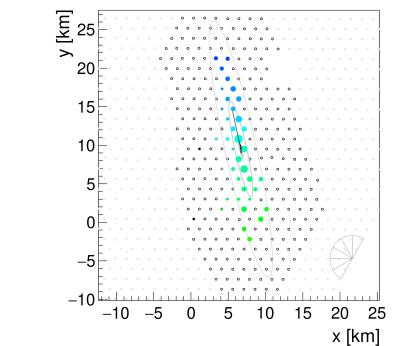
muon density map

$$\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi)$$
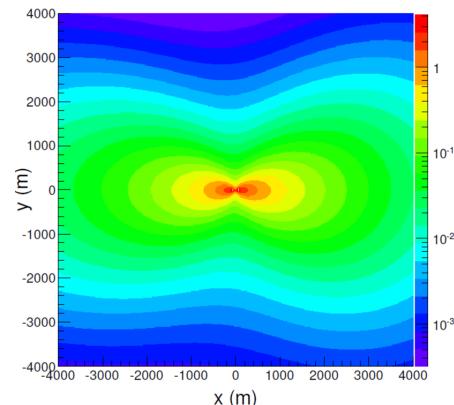
SD 750 m vertical
θ < 40°

S(450) – shower size

5
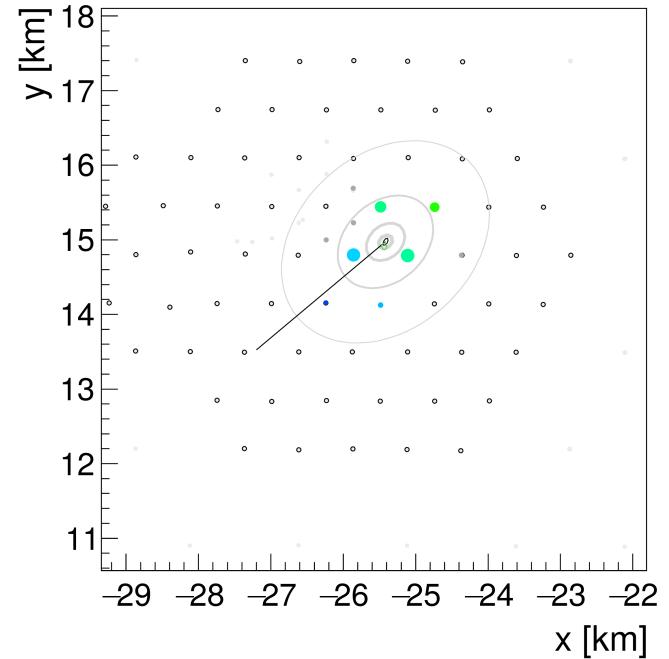
FD events

hybrid

camera view
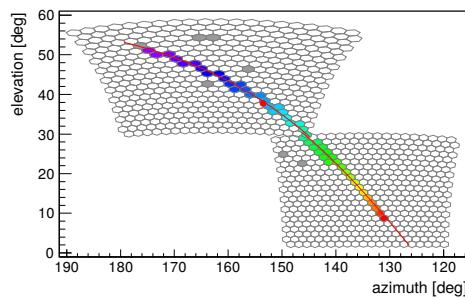
light flux profile
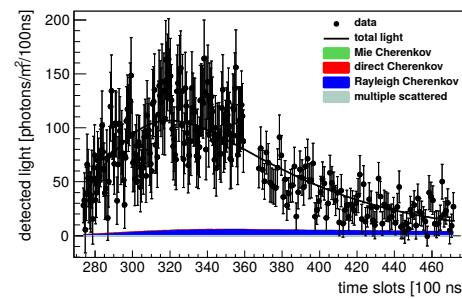
energy deposit profile
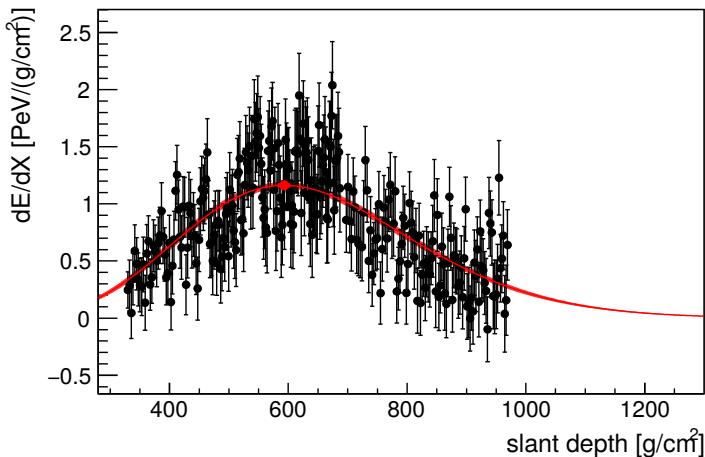
Cherenkov-dominated

### camera view

light flux profile

energy deposit profile

6
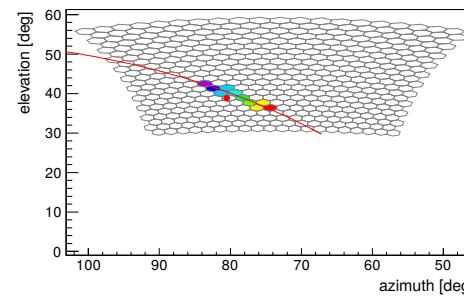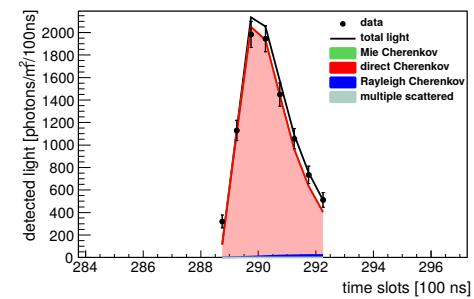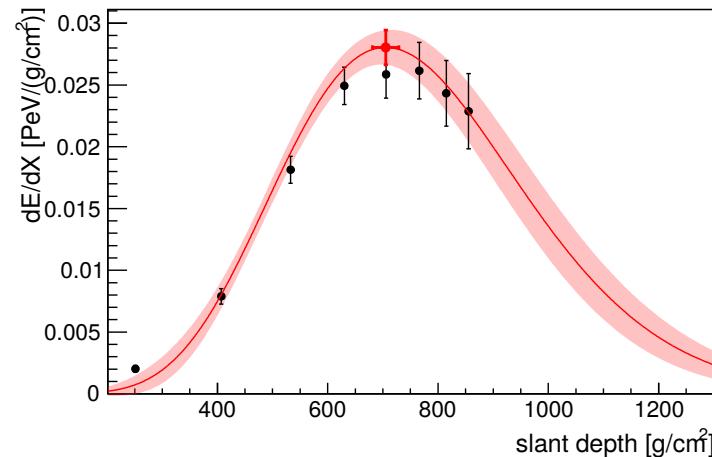
Calibration of SD events
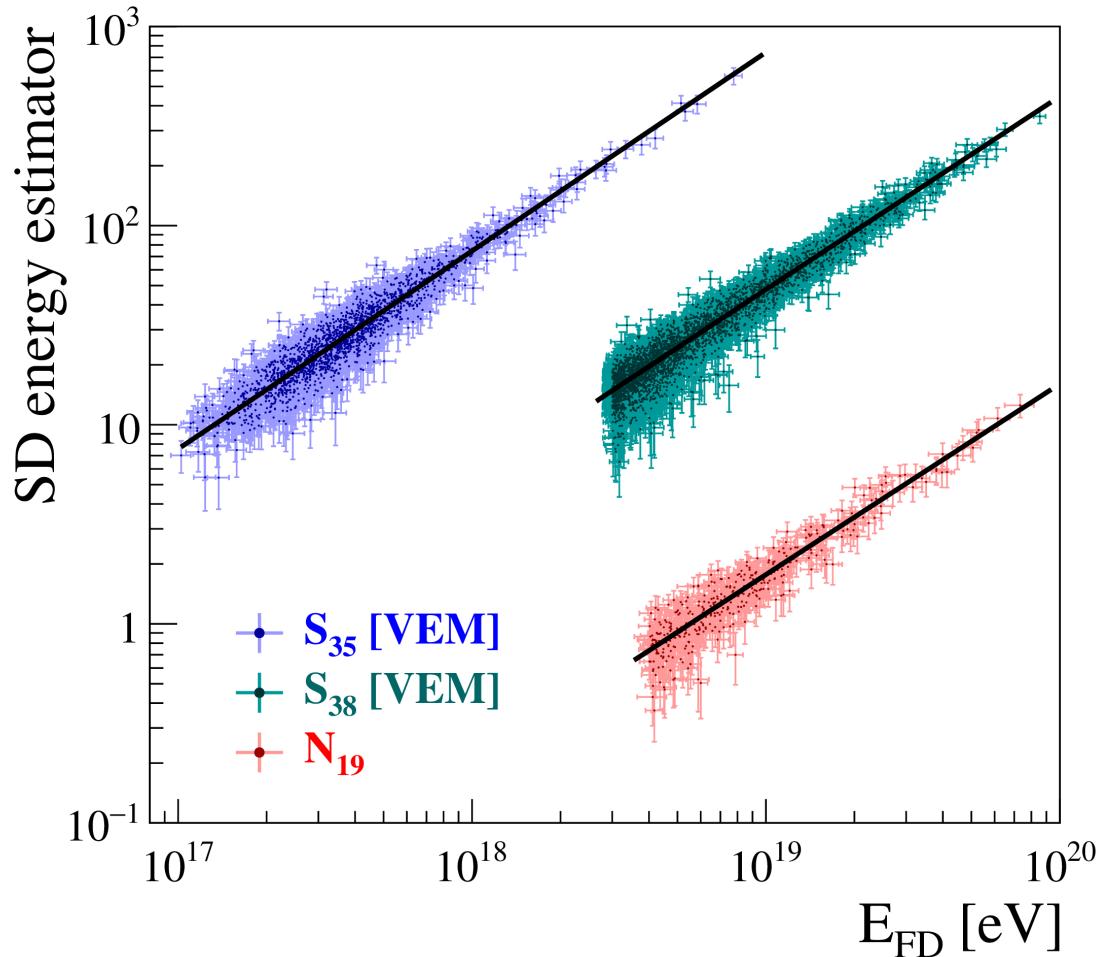
SD data are calibrated to FD energies - common energy scale

SD 1500 m vertical – S_{38}
- S(1000)+CIC
- threshold 2.5 EeV

SD 750 m – S_{35}
- S(450)+CIC
- threshold 0.1 EeV

SD 1500 m inclined – N_{19}
- scaling parameter
- threshold 4 EeV

Cherenkov-dominated data set

period: 06/2012 - 12/2017
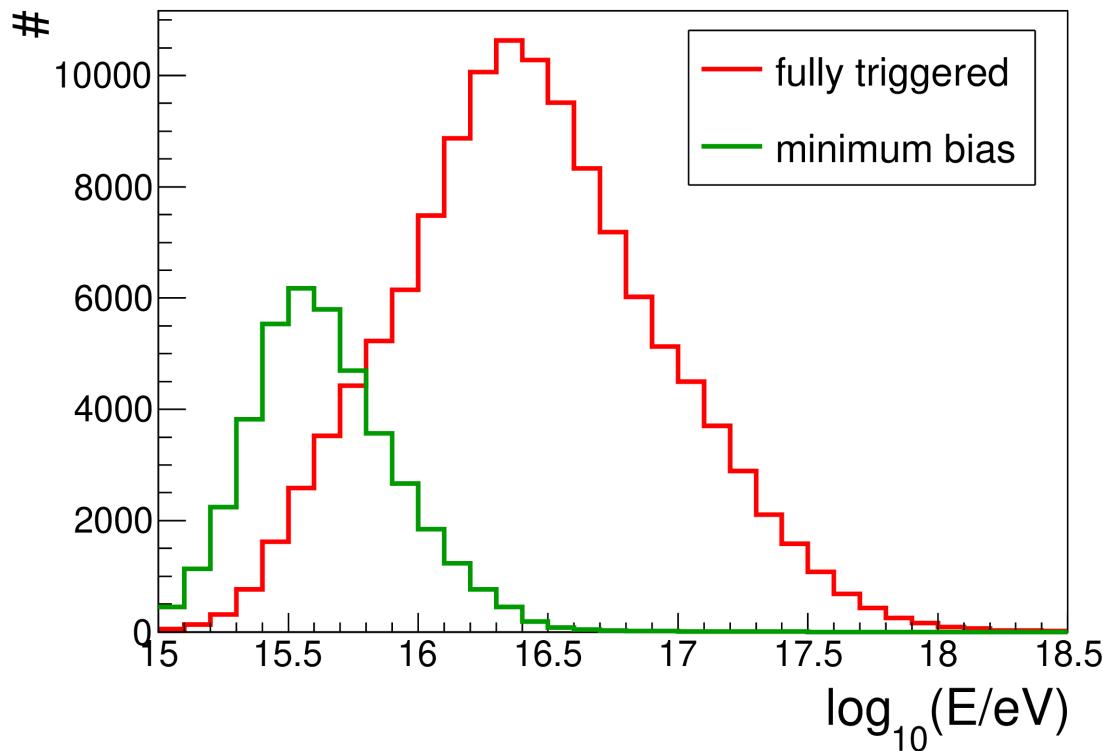
HEAT + Coihueco site telescopes
 - events reconstructed using
    Profile-constrained Geometry Fit[*]

fully triggered + minimum bias data
 - 10% of partially triggering data
 - trigger designed to suppress
    Cherenkov-dominated events

energy threshold decreased to 6 PeV
 - due to Cherenkov beam
 - limited by exposure systematics

[*] R. U. Abbasi et al. [HiRes Coll.], Phys. Rev. Lett. 100 (2008) 101101

[*] V. Novotný [for the Pierre Auger Coll.], Proc. 36th Int. Cosmic Ray Conf., Madison, USA (2019), PoS(ICRC2019)374

Exposure
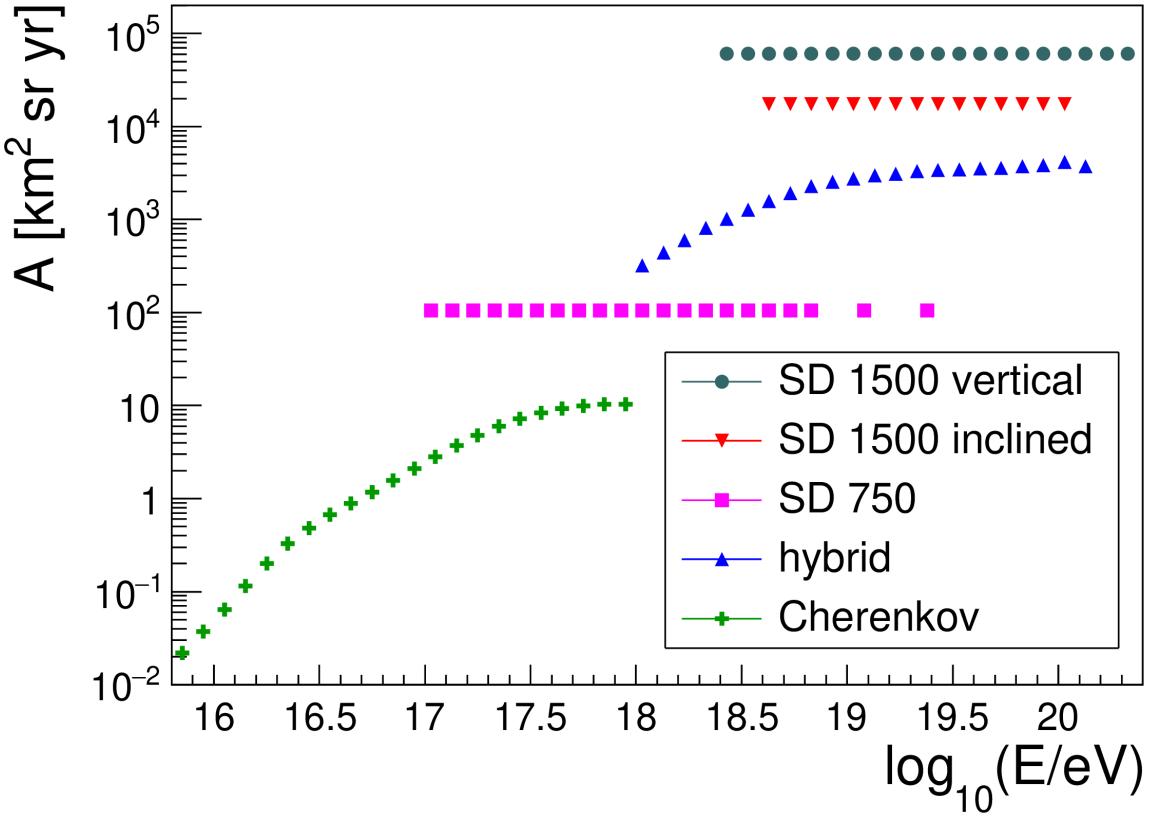
SD – from active hexagon cells
- geometrical calculation
- flat above threshold

FD – realistic MC simulations
- light from EAS
- atmospheric conditions
- detector status
- evolves with energy

contributions to tolal exposure @ 10^{19} eV:

SD 1500 m vertical	74.8%
SD 1500 m inclined	21.6%
SD 750 m	0.1%
hybrid	3.4%
Cherenkov	0%

9

Exposure – Cherenkov-dominated events

Mass composition uncertainty

- benchmark from Global Spline Fit[*] model
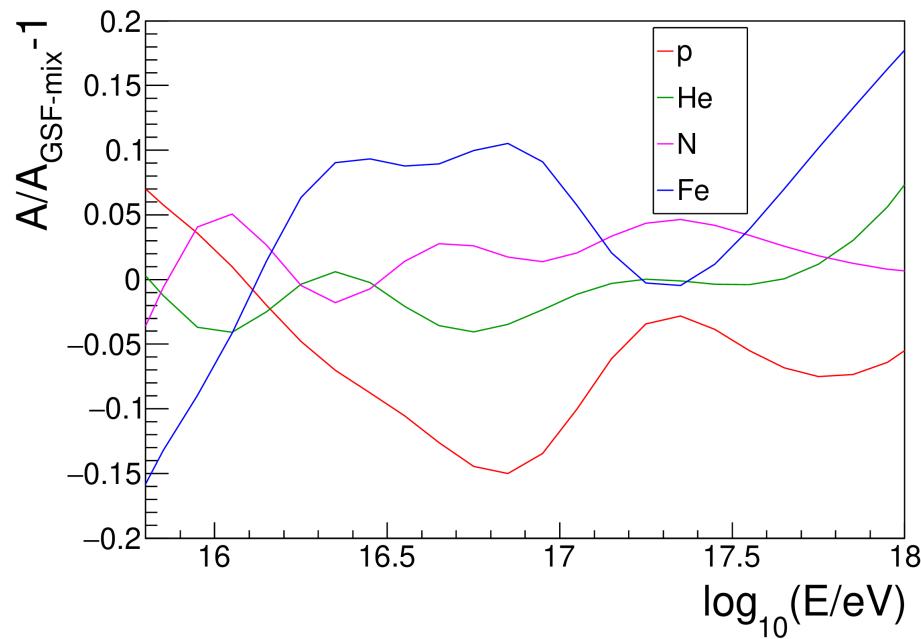
Fiducial volume cuts on shower geometry

- reduce exposure uncertainty from energy scale
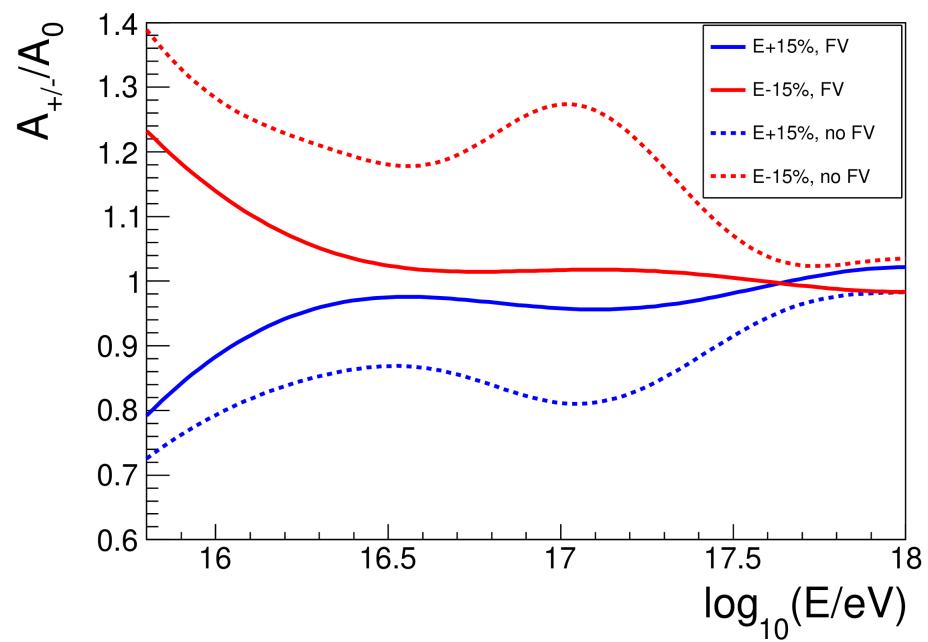
[*] H. P. Dembinski et al., Proc. 35th Int. Cosmic Ray Conf., Busan, Korea (2017), PoS(ICRC2017)533

Cherenkov-dominated spectrum

energy scale unc. – 15% for Cherenkov
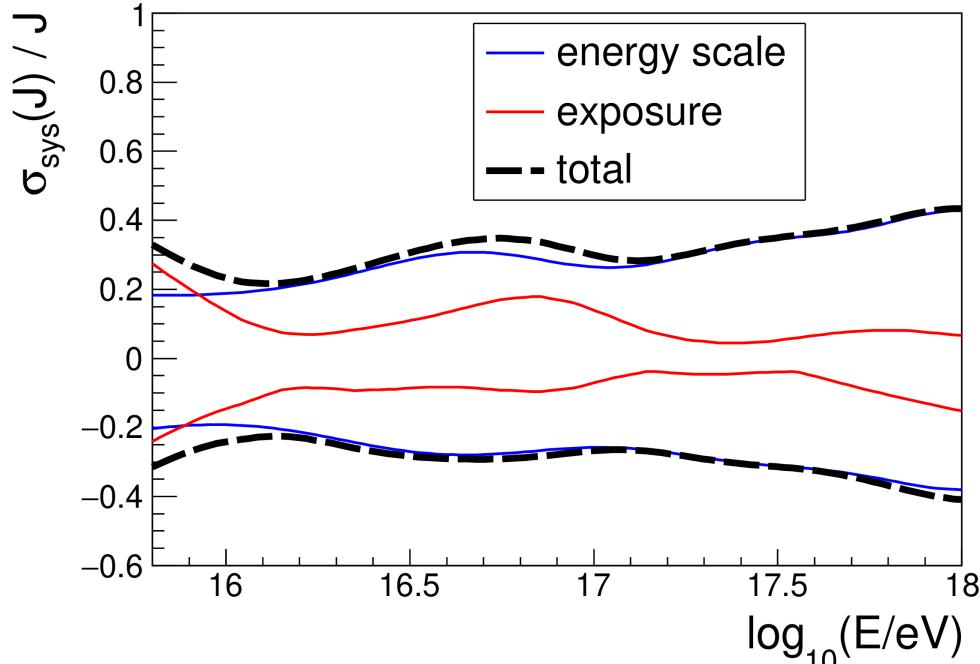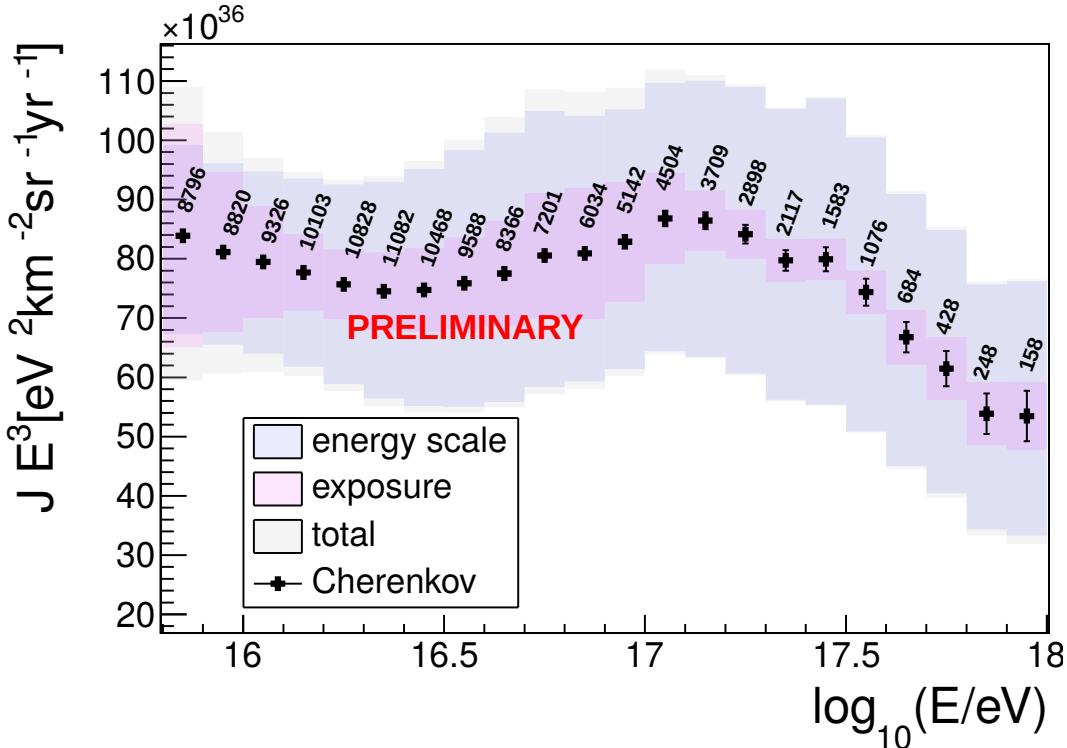
Auger measurements

compatible within uncorrelated uncertainties

normalization shifts after comb.:

|	
SD 1500 m	<1 %
SD 750 m	-2 %
SD 1500 m inclined	+5 %
Hybrid	<1 %
Cherenkov	+7 %
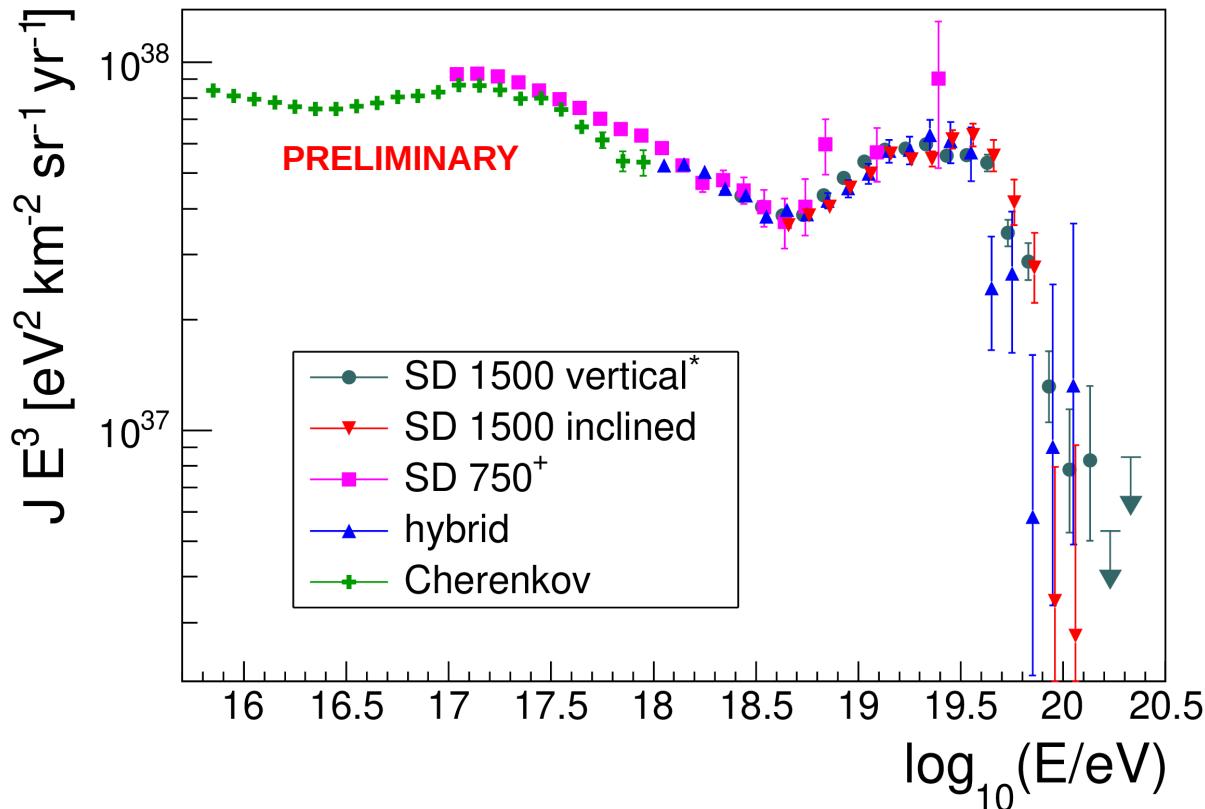
* A. Aab et al. [Pierre Auger Coll.], Phys. Rev. D102(2020) 062005

* A. Aab et al. [Pierre Auger Coll.], Phys. Rev. Lett.125(2020) 121106   + A. Aab et al. [Pierre Auger Coll.], submitted to Eur. Phys. J. C

Combined spectrum

likelihood of combination fit = exposure shifts x energy calibration shifts x forward-folding

description of data sets by model
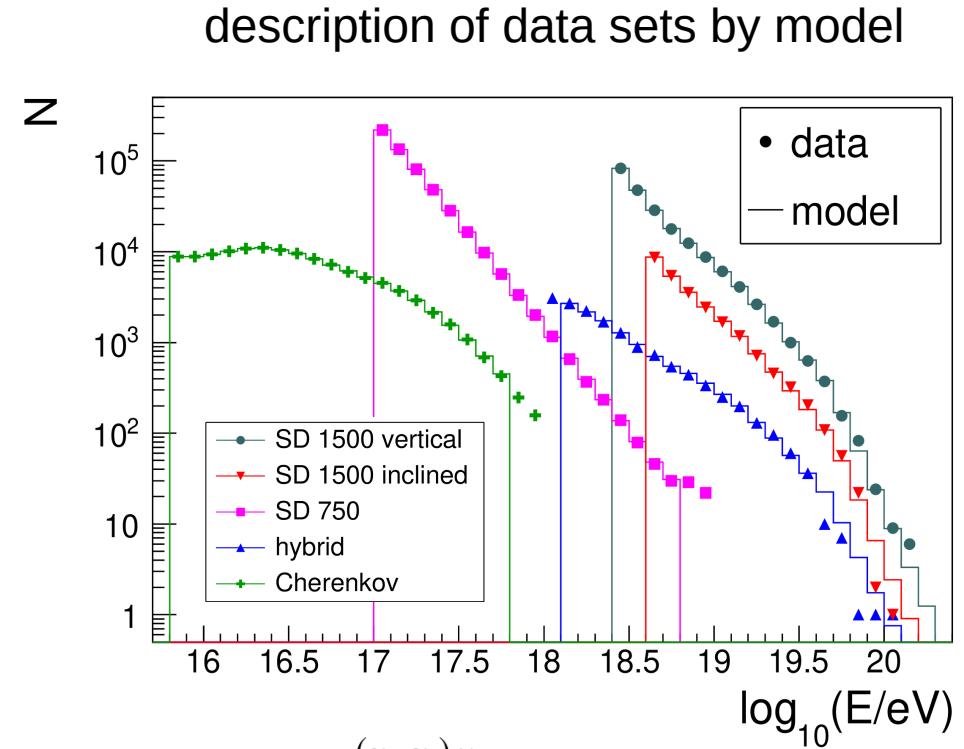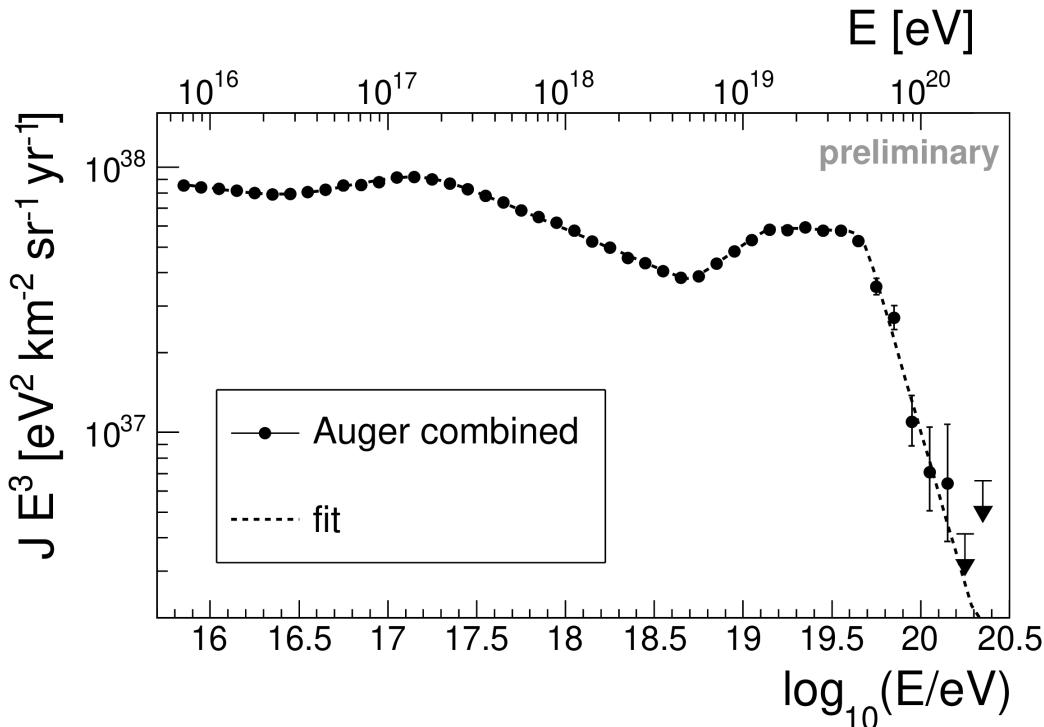
fit function: $J(E) = J_0 \left(\dfrac{E}{10^{16}\ \mathrm{eV}} \right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\dfrac{E}{E_{ij}} \right)^{\frac{1}{\omega_{ij}}} \right]^{(\gamma_i - \gamma_j)\,\omega_{ij}}, \ j = i + 1$

13

Spectral features
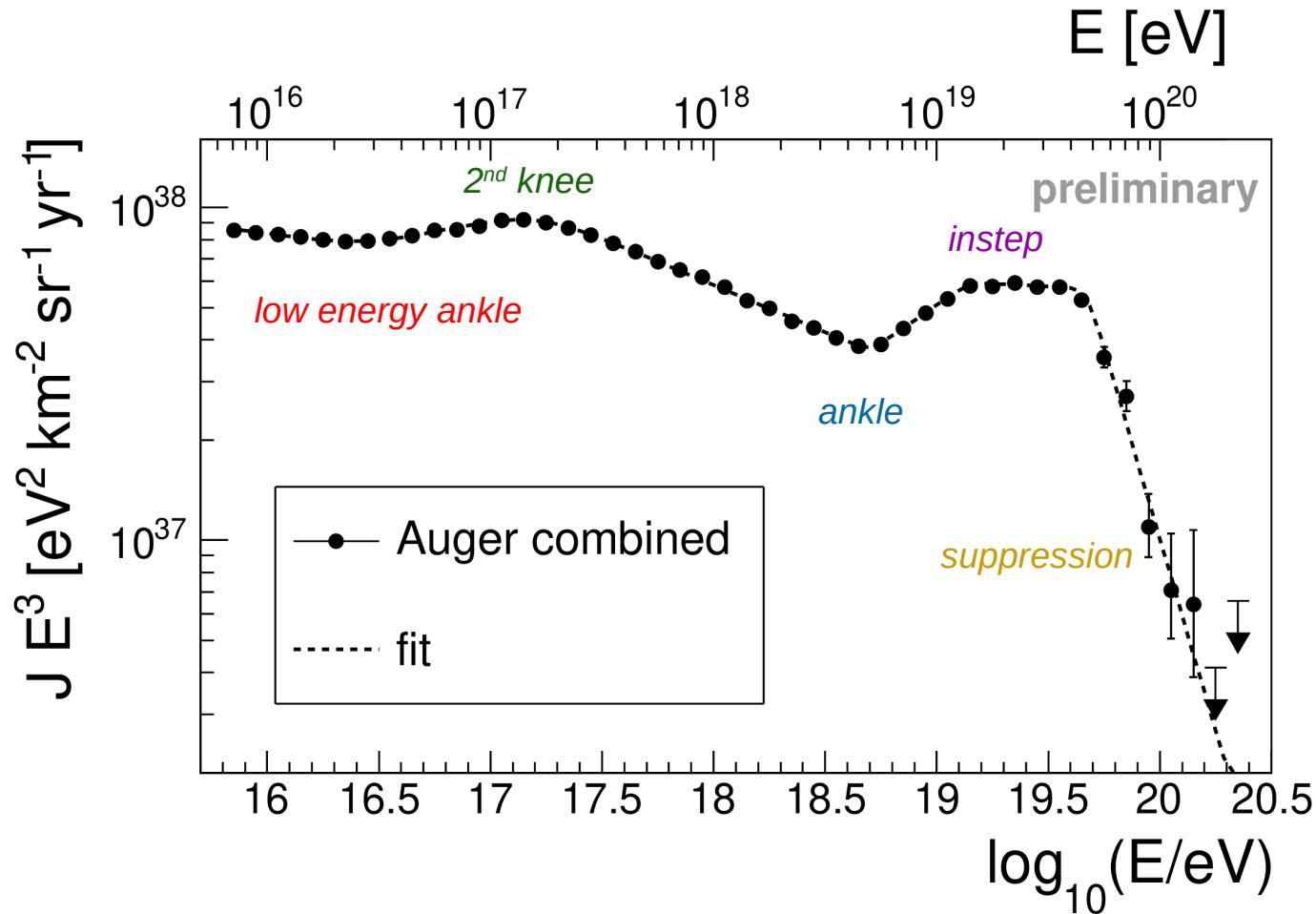
fit parameters (± stat. ± syst.)

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$

$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV

$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$

$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV

$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km^{-2} sr^{-1} yr^{-1} eV^{-1}

14

Summary

- energy spectrum estimated from **5 measurements**

  - three from SD – precisely defined exposure, large statistics

  - two from FD – nearly calorimetric measurement of energy

  - all have **common energy scale**

- estimates **combined into a single result**

  - extends from **6 PeV up to the highest energies**

- energy **threshold decreased by Cherenkov-dominated data**

  - basic systematics addressed

  - calibration of HEAT was improved wrt. ICRC 2019

- **low-energy ankle observed**

  - mass composition below 0.1 EeV to be studied

Backup

Combined spectrum – systematic uncertainty
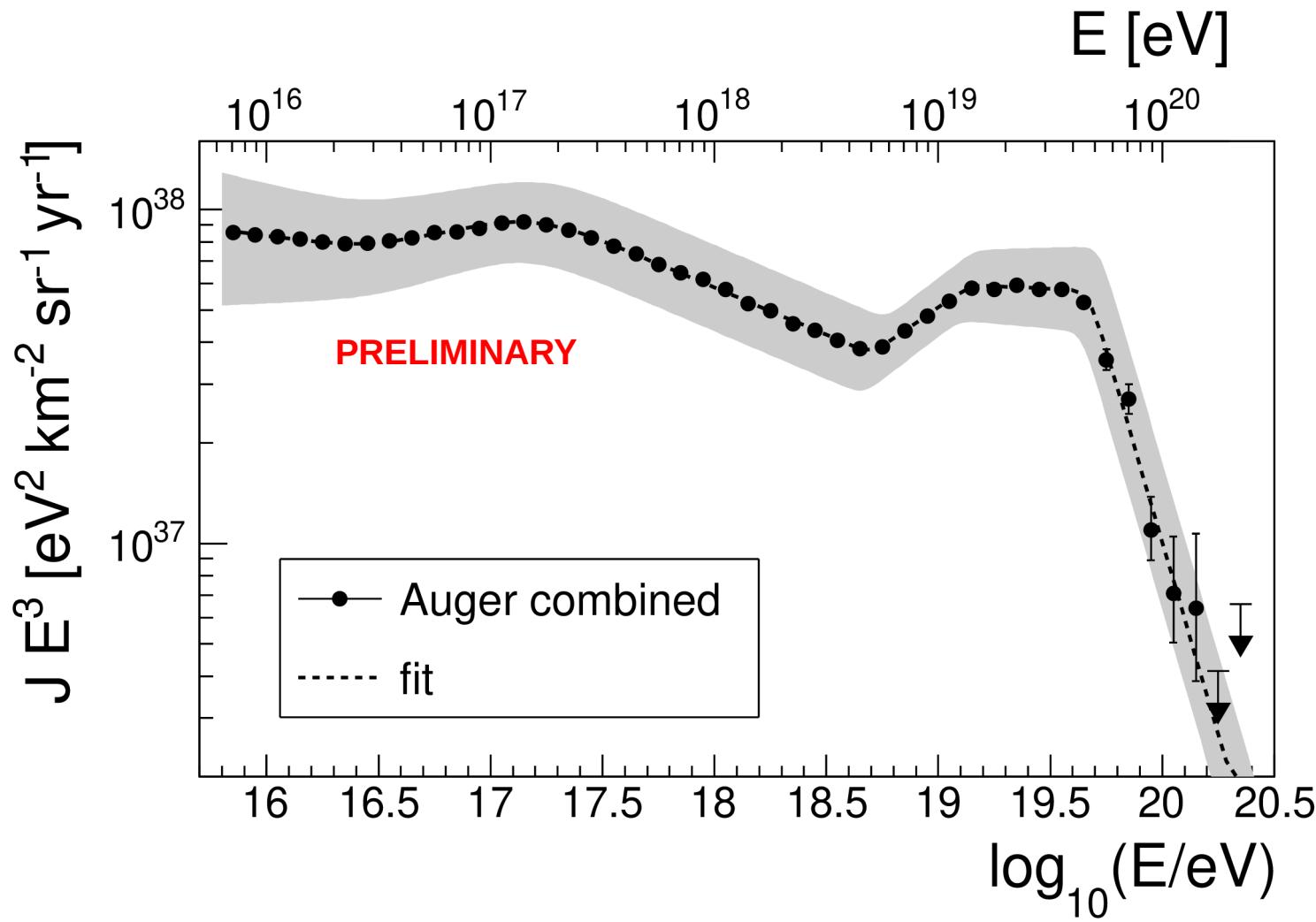
Comparison with other experiments

Legend:
- ● **Auger (2021)**
- ● **TA SD (2019)**
- ■ **TA TALE (2018)**
- ▼ **TUNKA-133 (2020)**
- ▲ **Yakutsk (2015)**
- ✤ Ice Top (2019)
- □ KAS. Gr. EPOS-LHC (2015)
- △ KAS. Gr. QGSII-04 (2015)
- ◇ Tibet-III (2008)
- ★ GAMMA (2014)
- ★ AKENO (1992)

calorimetric in colour
MC based in gray
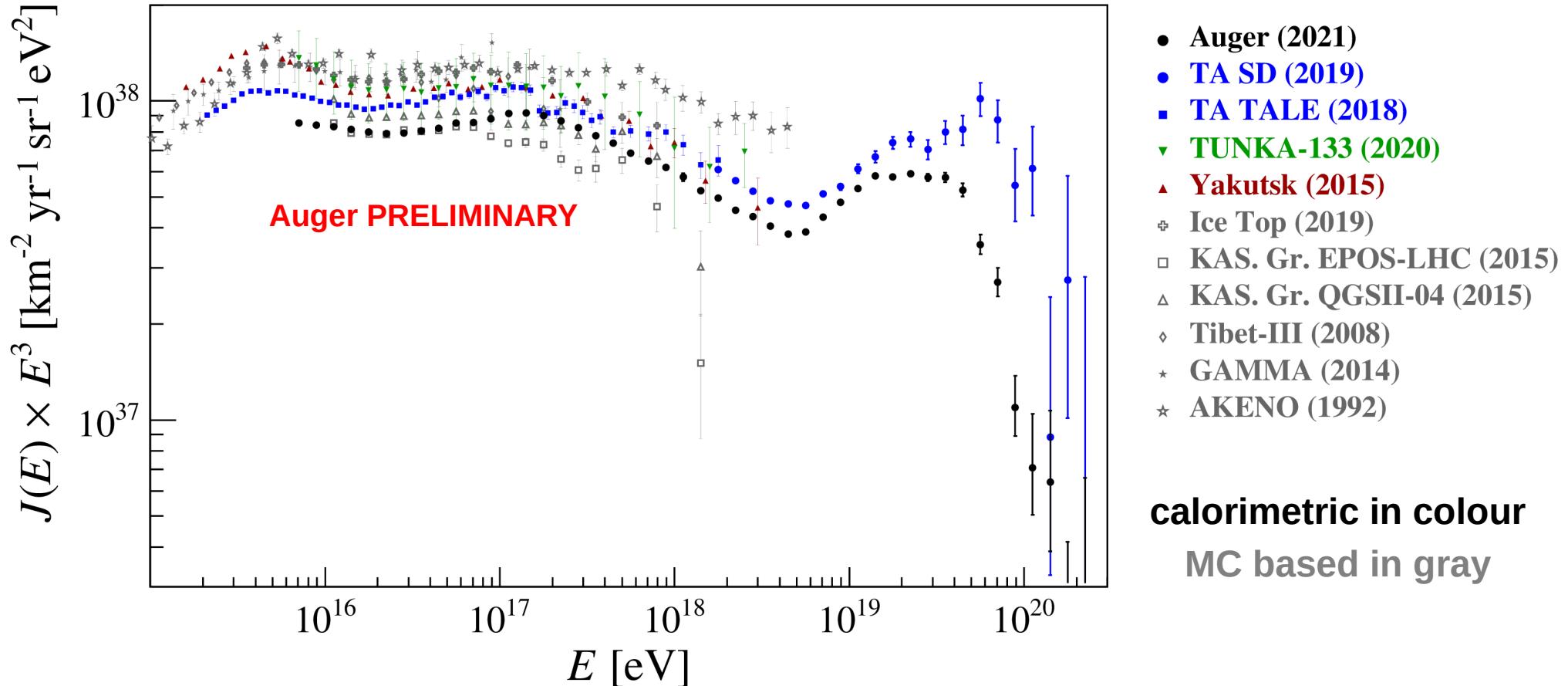
Auger PRELIMINARY

Normalization of Auger Observatory preliminary result at low energy will be investigated.   18

Comparison of Cherenkov and SD 750 m