The Cosmic Ray Flux Spectrum above 300 PeV of the Pierre Auger Observatory

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TeVPA

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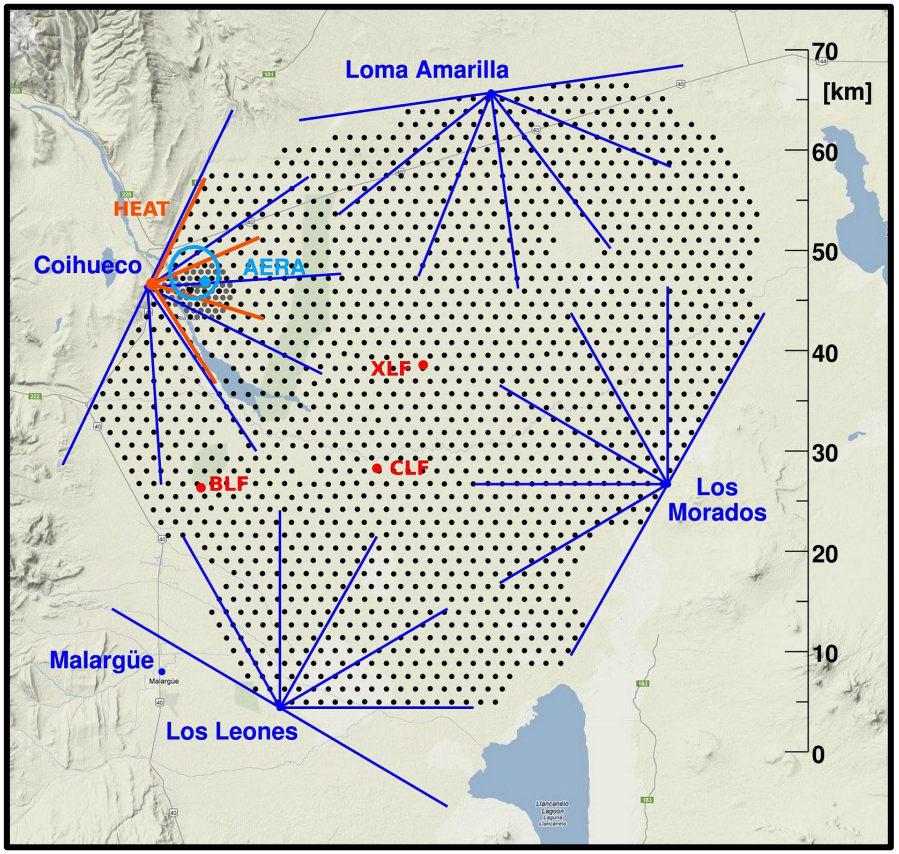
The Pierre Auger Observatory



Largest cosmic ray detector in the world - 3000 km^2

Running since 2004, completed 2008

Hybrid Detector

- Surface Water Cherenkov Detectors
- Fluorescence Telescopes

Surface Detector efficient above 3 EeV

Low energy extension to both arrays

- Higher angled telescope
- Denser surface detector array

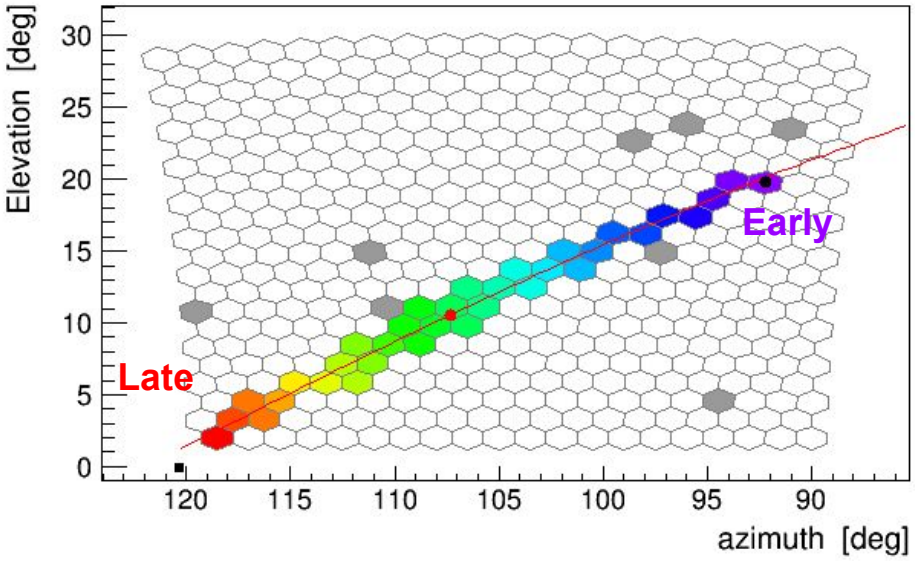
Fluorescence Detector (FD)

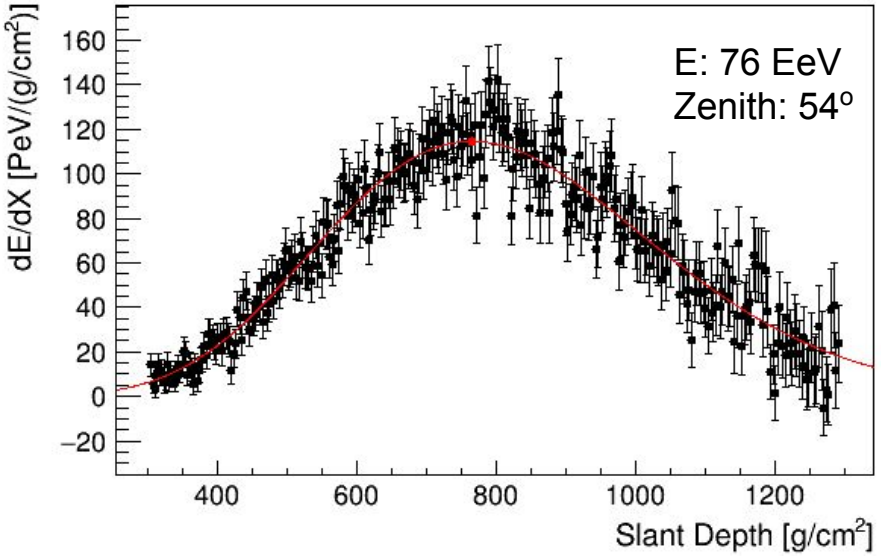
Four detector sites on edge of SD

Views shower development

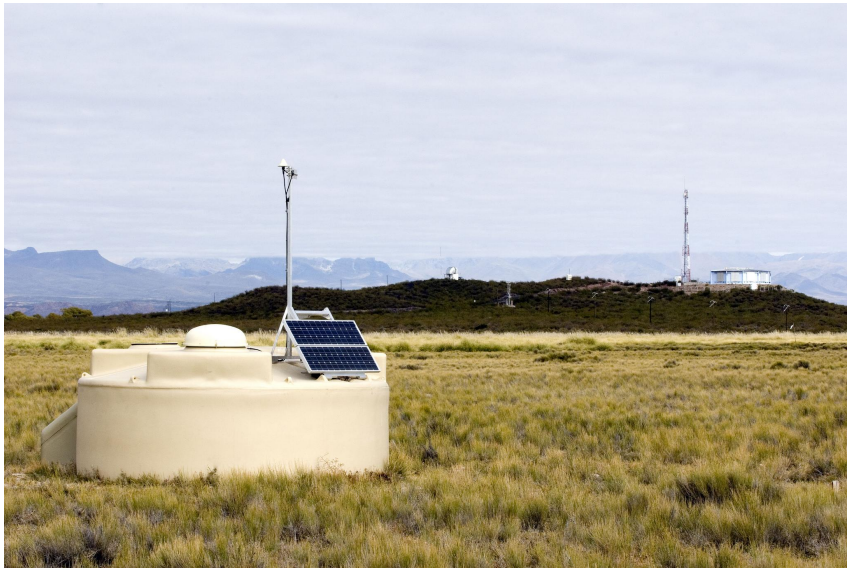
Calorimetric measurement of electromagnetic air shower

Provides energy scale





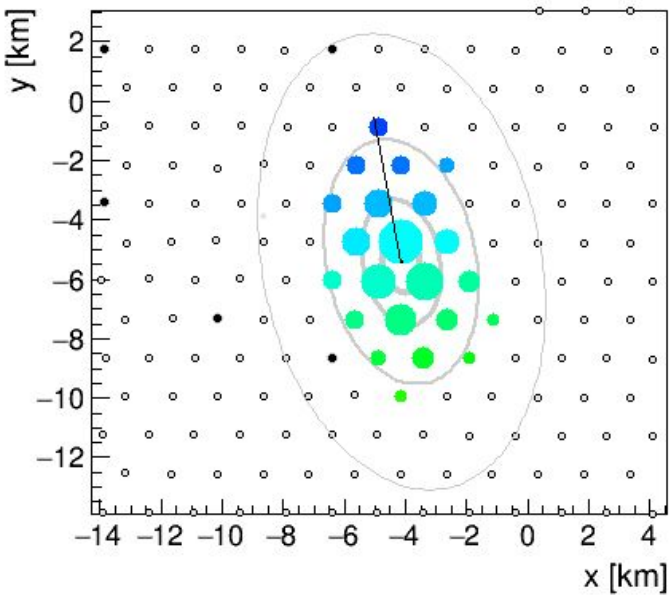
Surface Detector (SD)

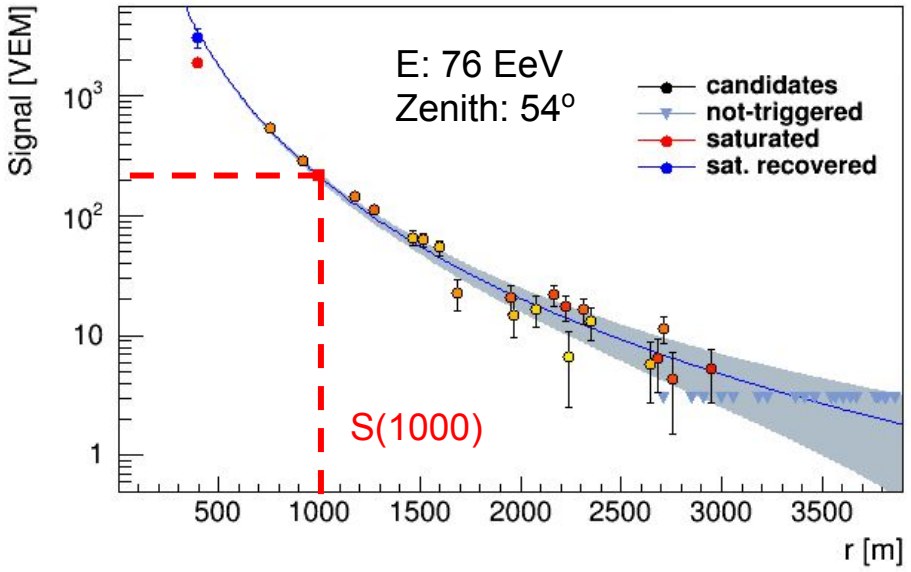


1600 (61) Water Cherenkov Detectors in hexagonal array with 1500 m (750 m) spacing

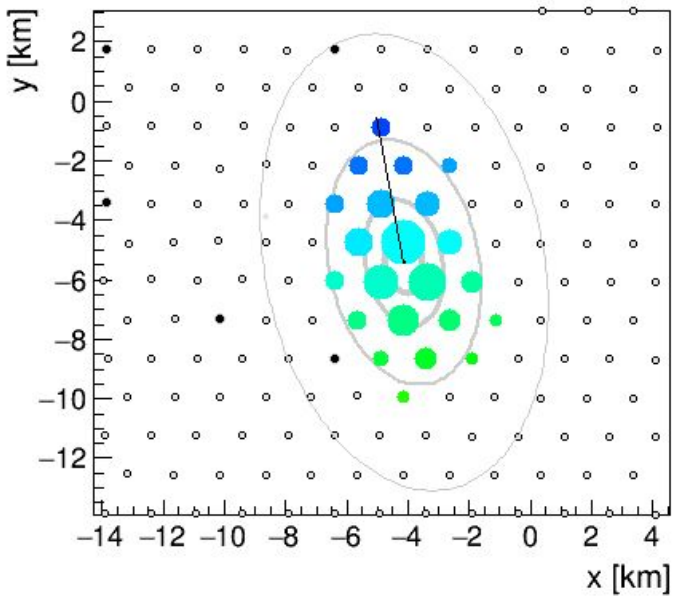
Measures density of secondary particles on the ground

Shower energy estimated from lateral distribution signal





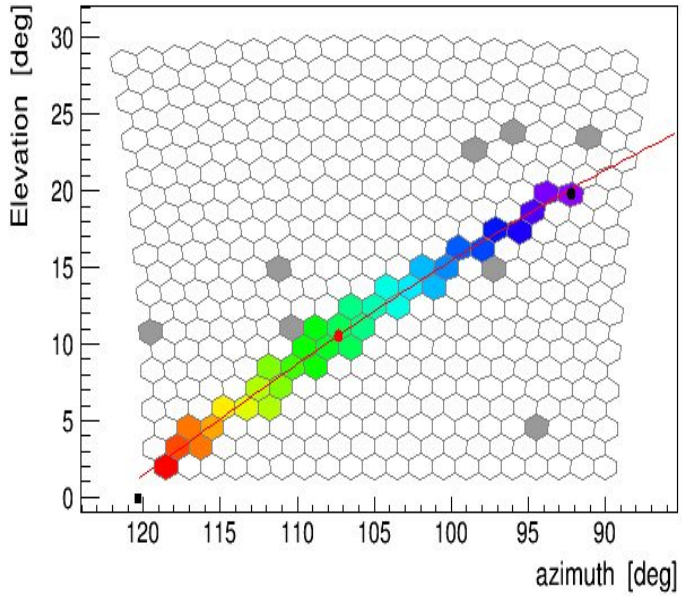
Event Reconstruction Types



SD Vertical, 1500 m
Energy: > 3 EeV
Zenith: < 60°
Exposure:
51,588 [km^2 sr yr]

SD Vertical, 750 m
Energy: > 300 PeV
Zenith: < 55°
Exposure:
228 [km^2 sr yr]

SD Inclined, 1500 m
Energy: > 4 EeV
Zenith: 60° - 80°
Exposure:
19,602 [km^2 sr yr]



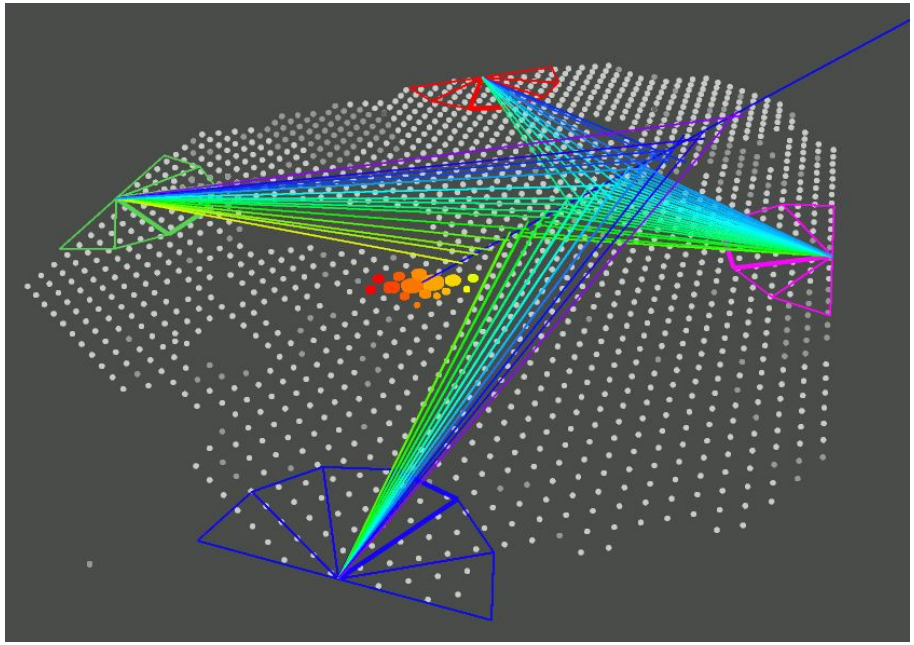
FD (Hybrid)
Energy: > 1 EeV
Exposure:
1946 [km^2 sr yr]

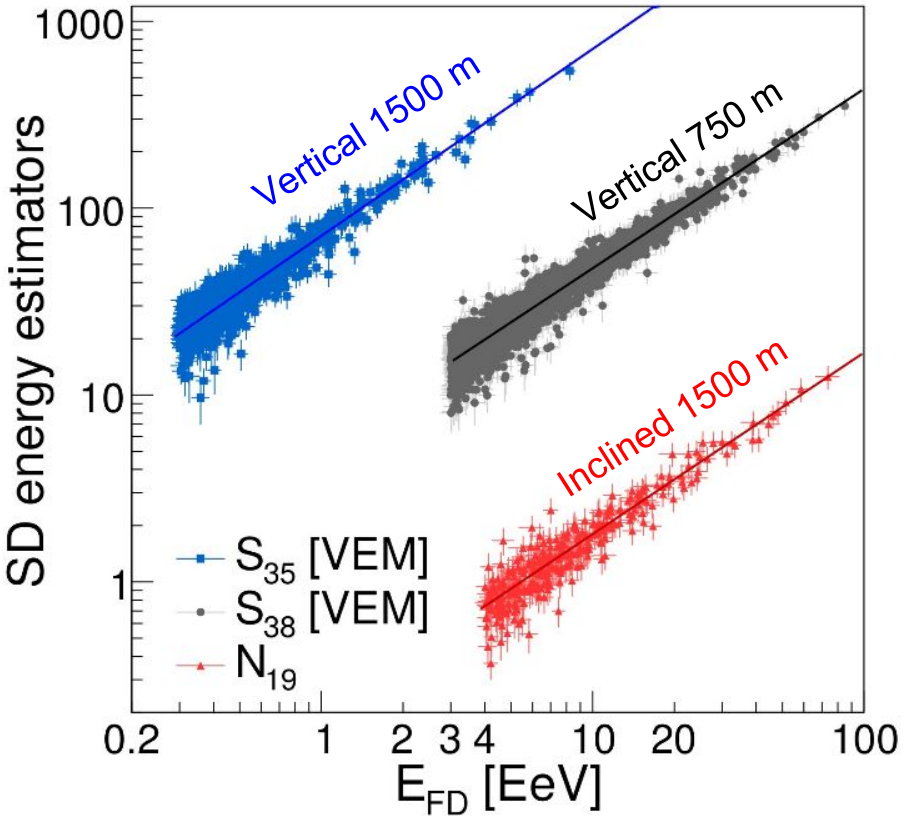
Energy Calibration

Uses events which are reconstructed by the FD *and* SD, independently

Provide a data set to calibrate the SD reconstructions

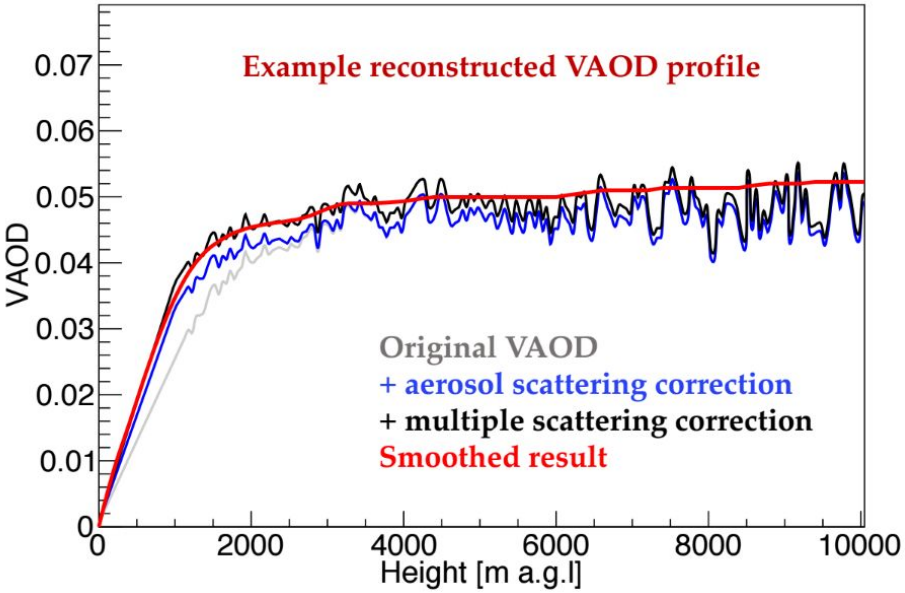
$E_{SD} = A\, X^{B}, \quad X = \{S_{35}, S_{38}, N_{19}\}$

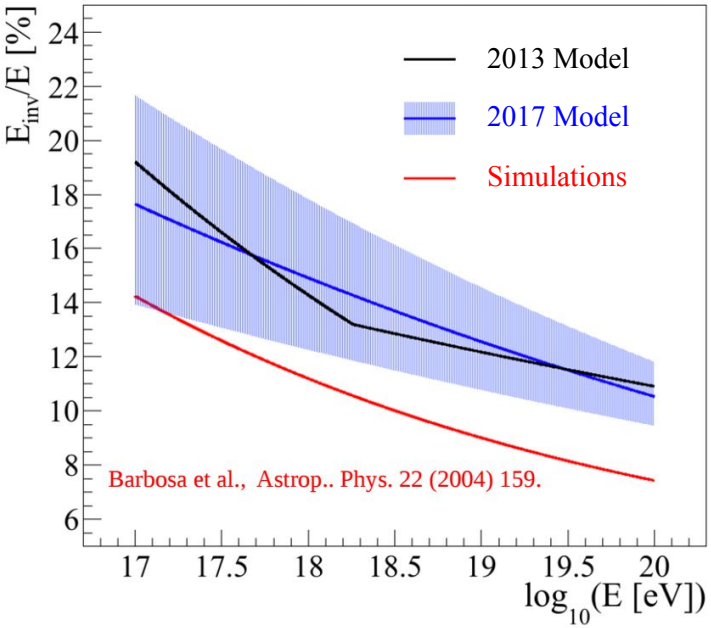




Recent Reconstruction Improvements

- Update to the modeling of the vertical aerosol optical depth (VAOD)
  - Single scattering from outside field of view
  - Multiple scattering of light
- Updated calculation of invisible energy
  - $E_{FD} = E_{Cal} + E_{Inv}$
  - Based on measured data instead of simulation
  - Comparable to previous invisible energy measurements

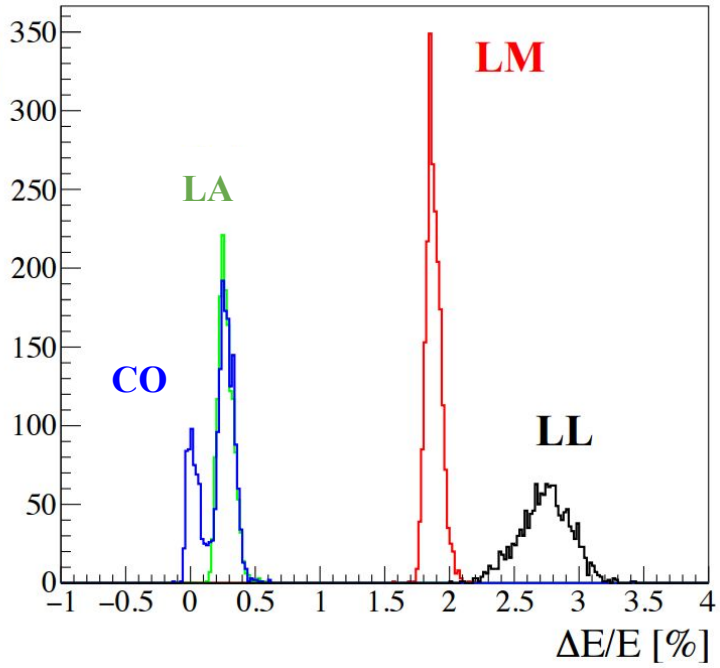




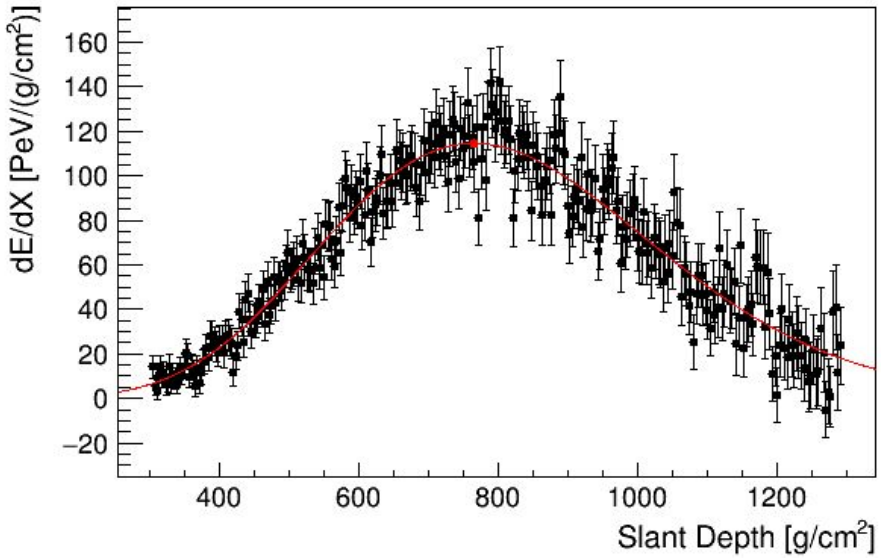
M. Malacari, PoS(ICRC2017) 398

Recent Reconstruction Improvements

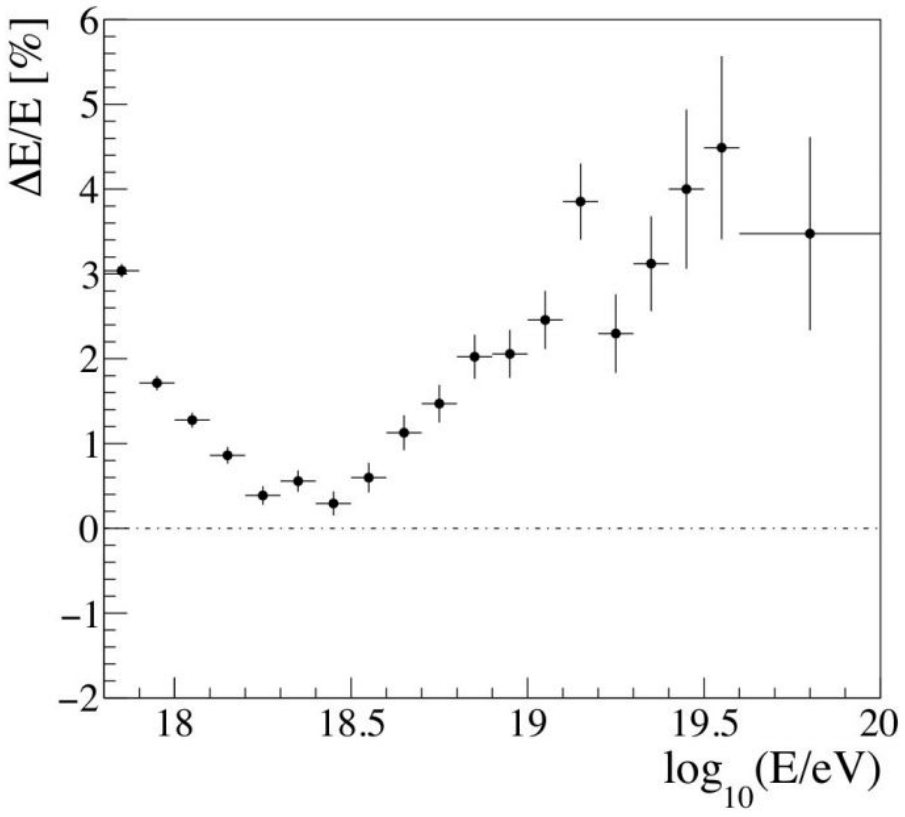
- Update to individual FD eyes
  - Recalculation of optical efficiency for each telescope separately
  - Improvement of the photomultiplier calibration



- Longitudinal profile fit
  - Removed bias in the longitudinal FD fit
  - Constraint on area-over-peak
  - Affects showers that are only observed near maximum
  - Affects showers < 1EeV



Impact On Observatory Energy Scale

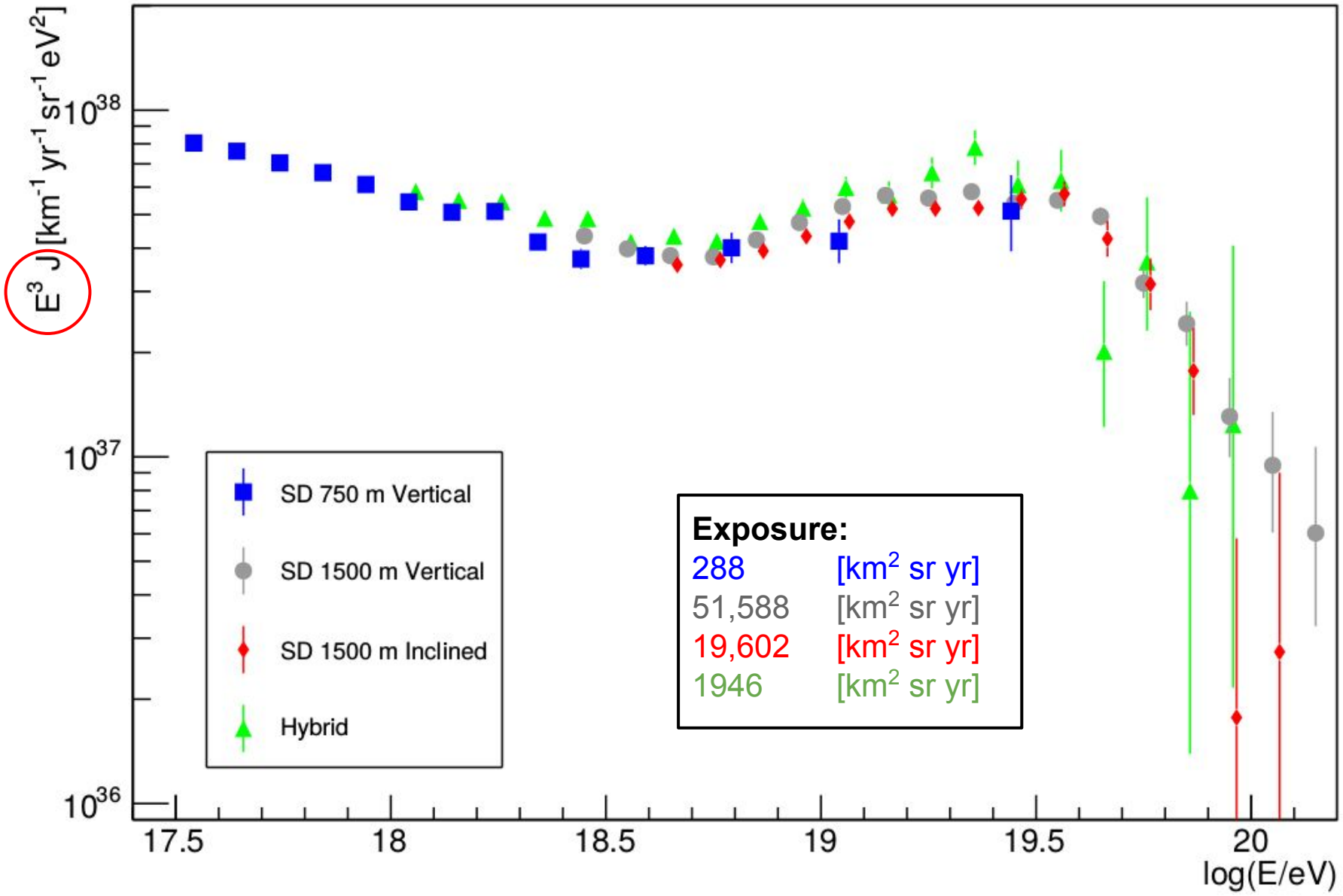


Systematic Uncertainties on the energy scale	
Fluorescence Yield	3.6%
Atmospheric Measurements	3.4% ÷ 6.2%
FD Calibration	9.9%
FD Profile Reconstruction	6.5% ÷ 5.6%
Invisible Energy	3% ÷ 1.5%
Other Contributions	5%
Total	**14%**

Verzi, Valerio. *Proceedings of the 33rd ICRC* (2013).

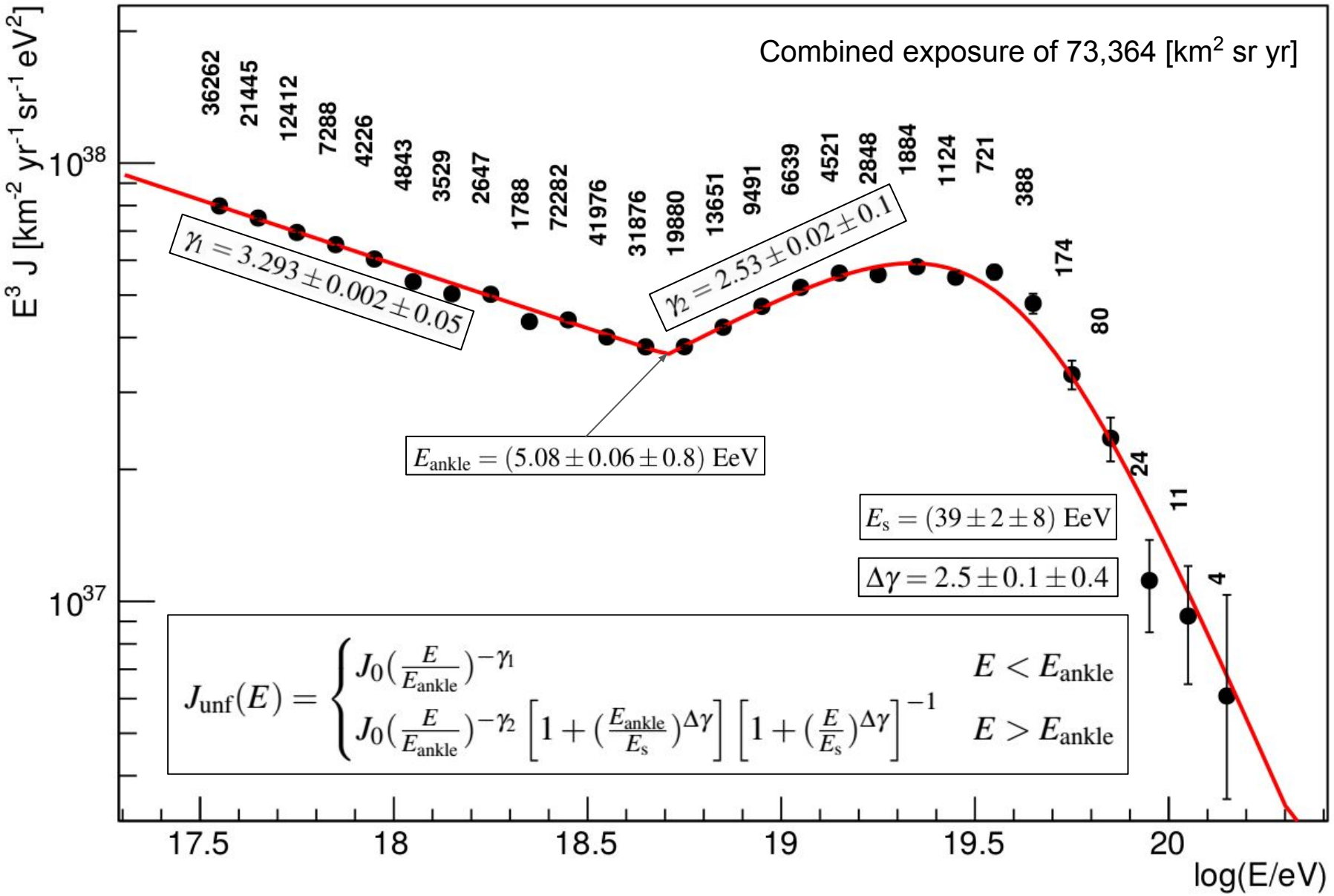
Total update to the energy scale well within the systematic uncertainties

Energy Spectrum



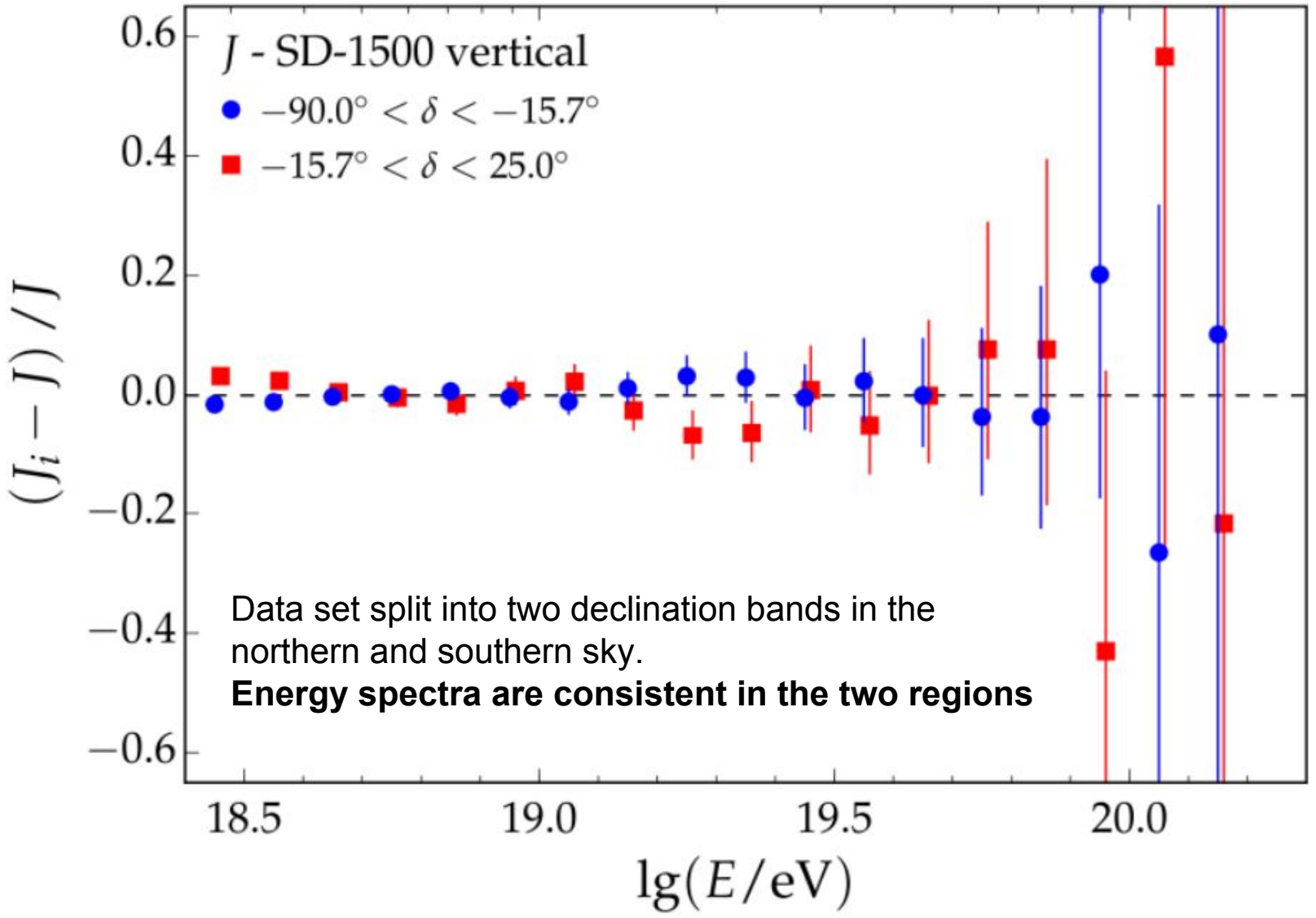
Only statistical errors shown

Combined Spectrum and Fit



Only statistical errors shown

Declination Dependence



Conclusion

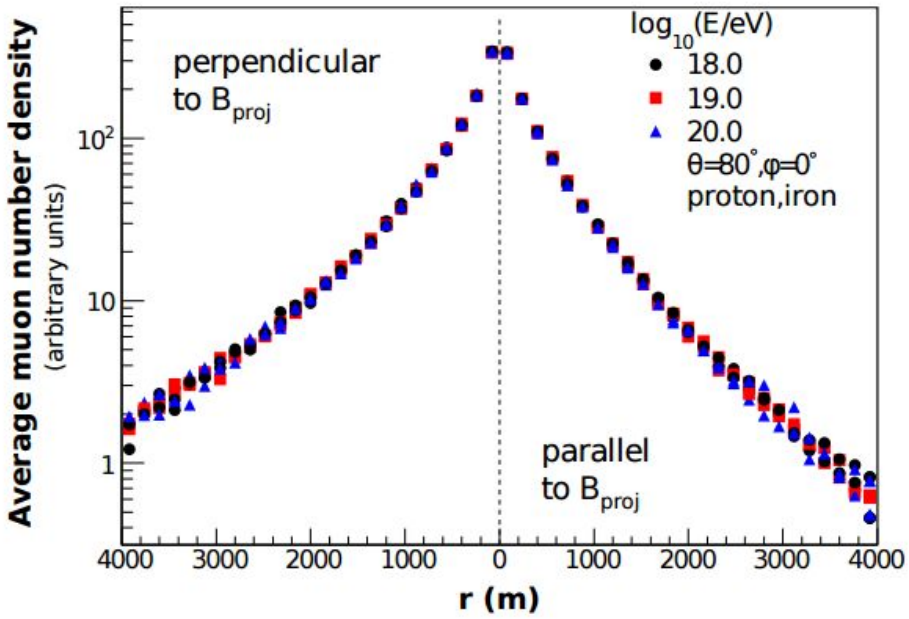
- Many recent improvements to the FD reconstruction
  - Upward shift in the energy scale <=4% (within 14% systematic error)
- Four different methods to measure the cosmic ray flux for energies above 300 PeV
- The spectral features have been measured using the combined energy spectrum with over 70,000 [km^2 sr yr] of exposure
- Energy spectrum shows no declination dependence

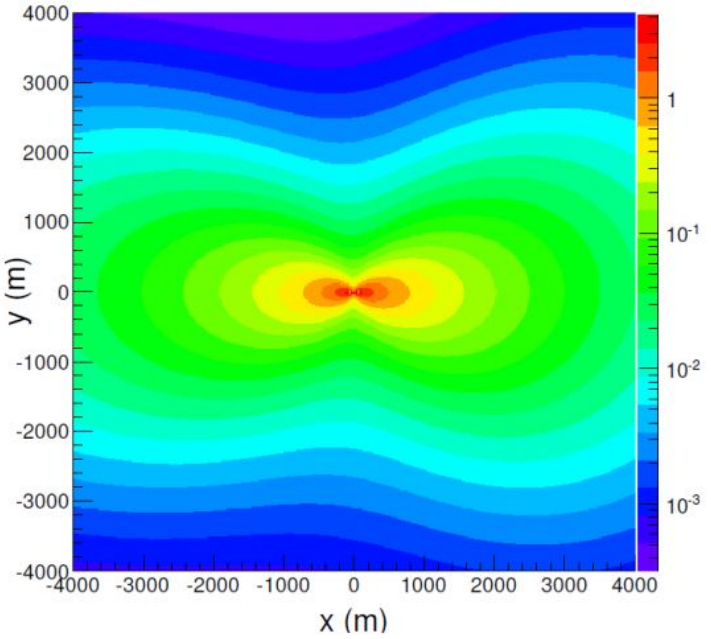
SD Inclined Event Reconstruction

The muonic component that reaches the ground has universal shape

Energy estimator given by relative muon density $\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi)$

N_{19} values calibrated with FD events





Pierre Auger Collaboration, JCAP 08 (2014) 019

SD Vertical Event Reconstruction

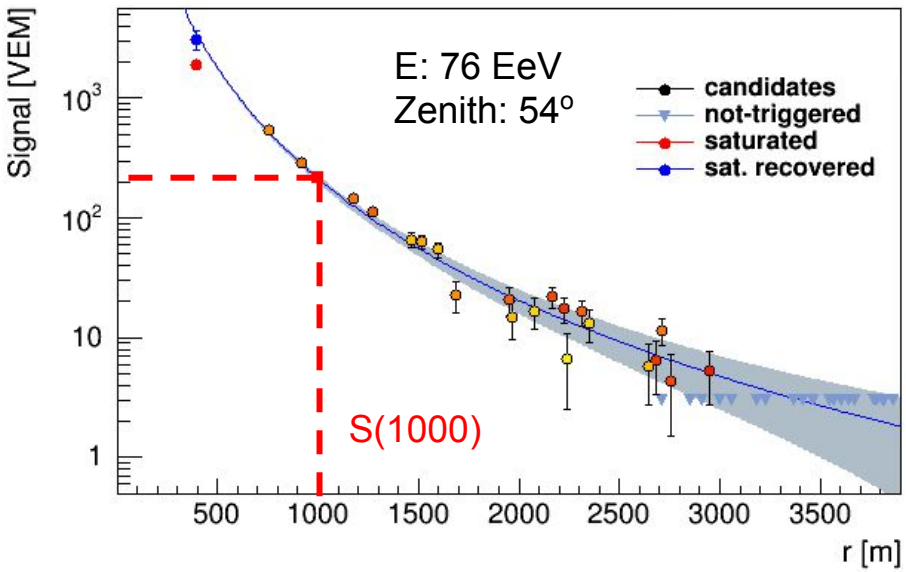
Vertical events fit to an empirical lateral distribution function

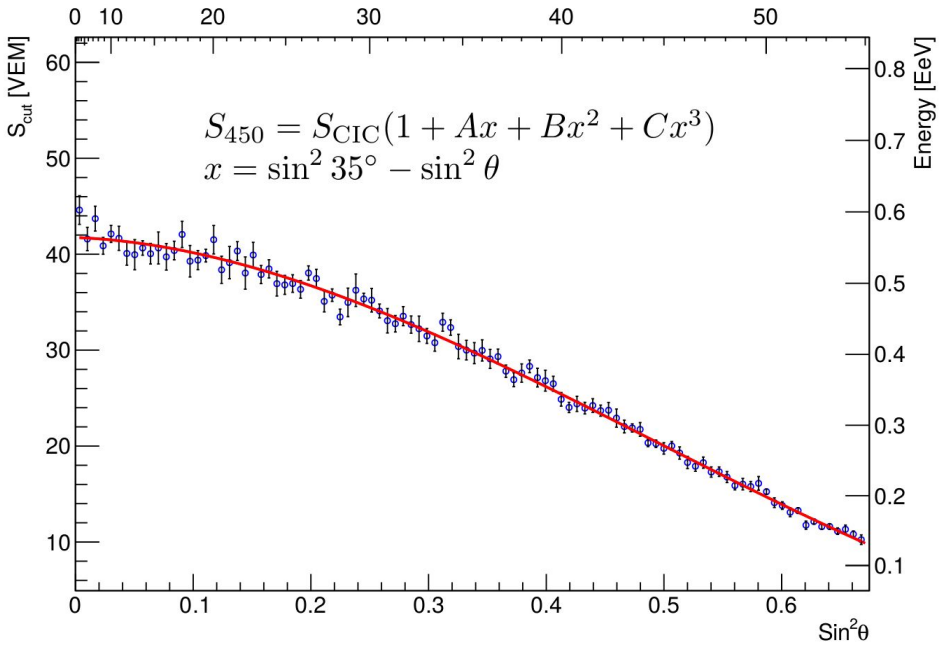
1st order energy estimator: S(1000) or S(450) given by signal at that dist.

Correct for geomagnetic and weather effects, a few percent

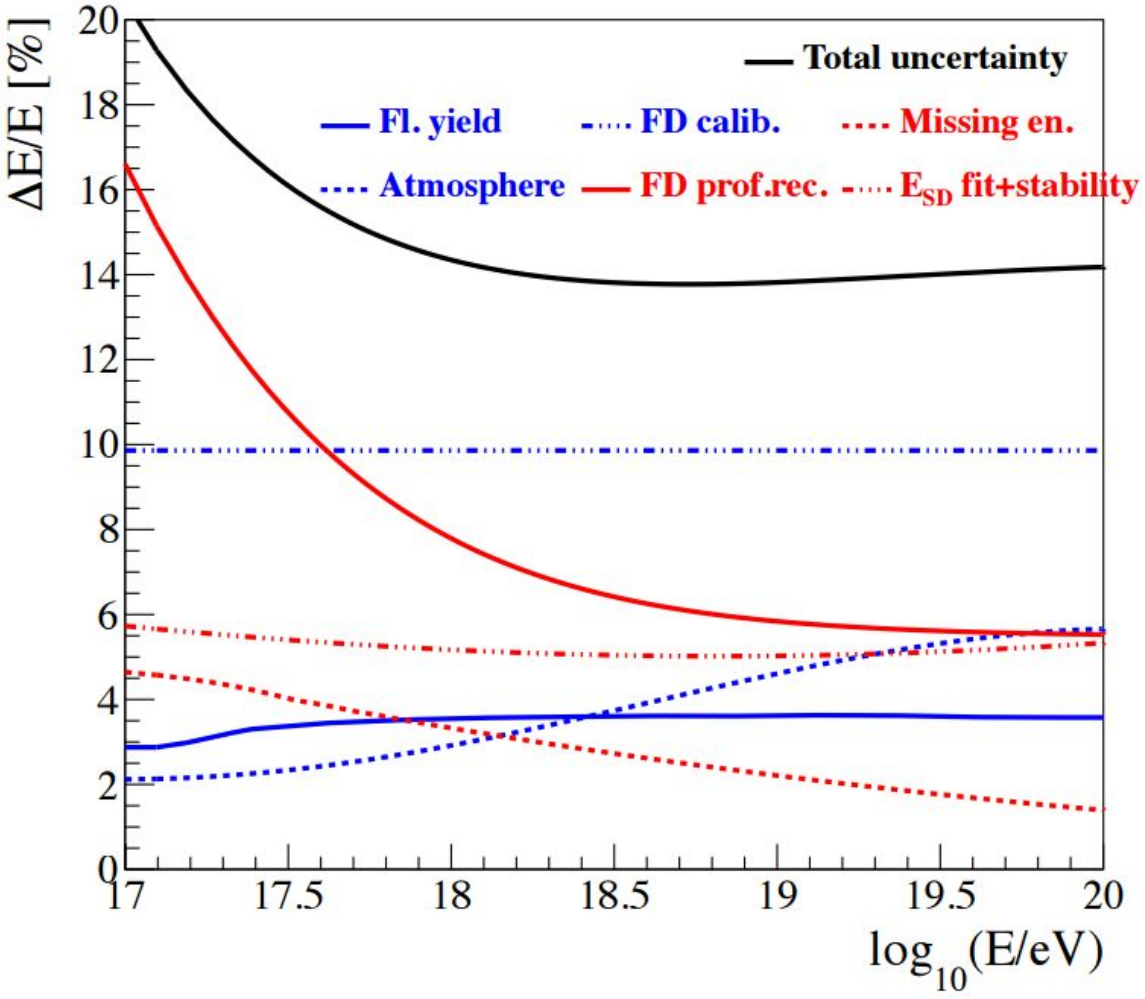
Apply zenith correction to account for different grammage traversed

Converts S(1000) → S_{38}, S(450) → S_{35}

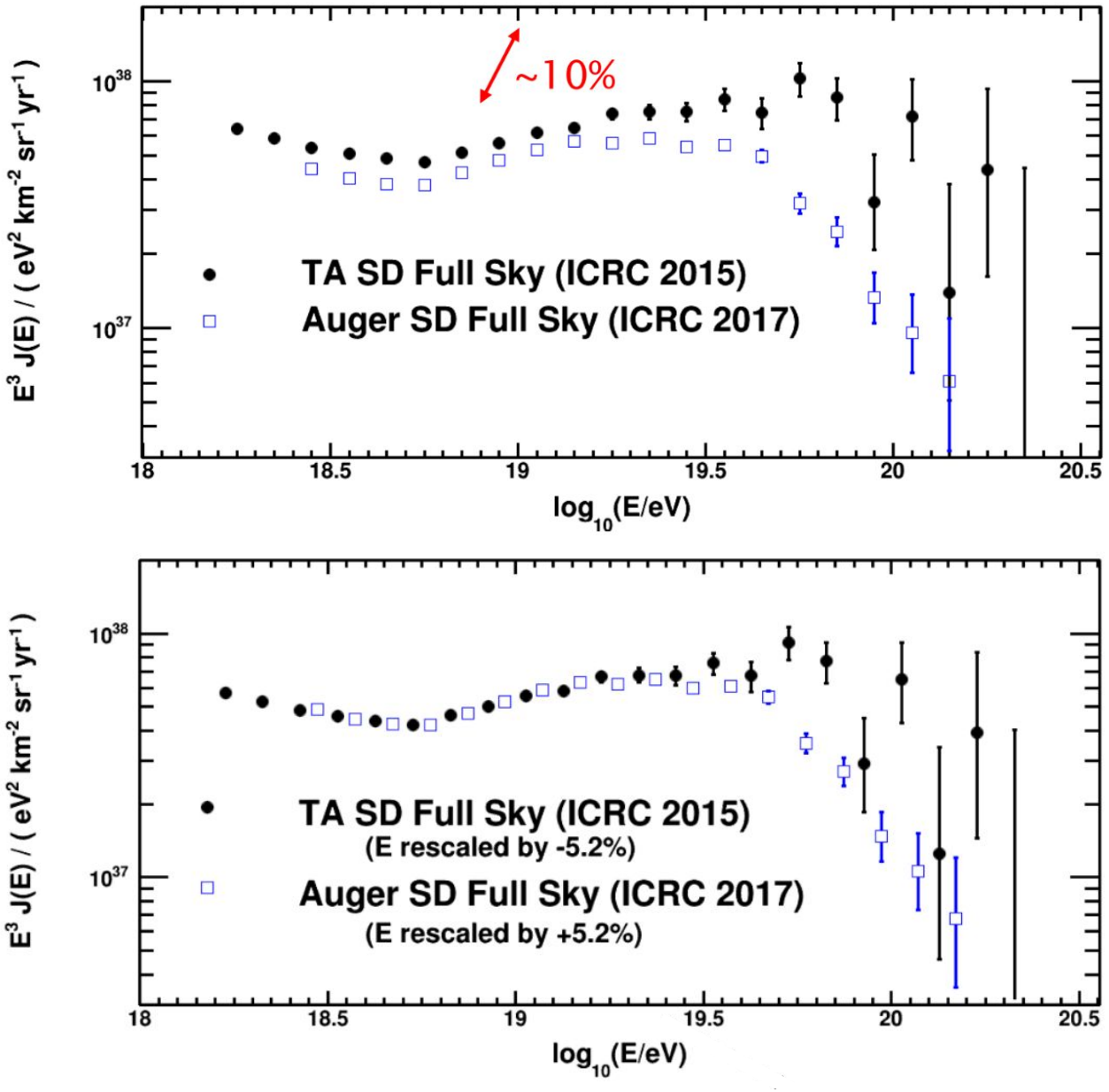




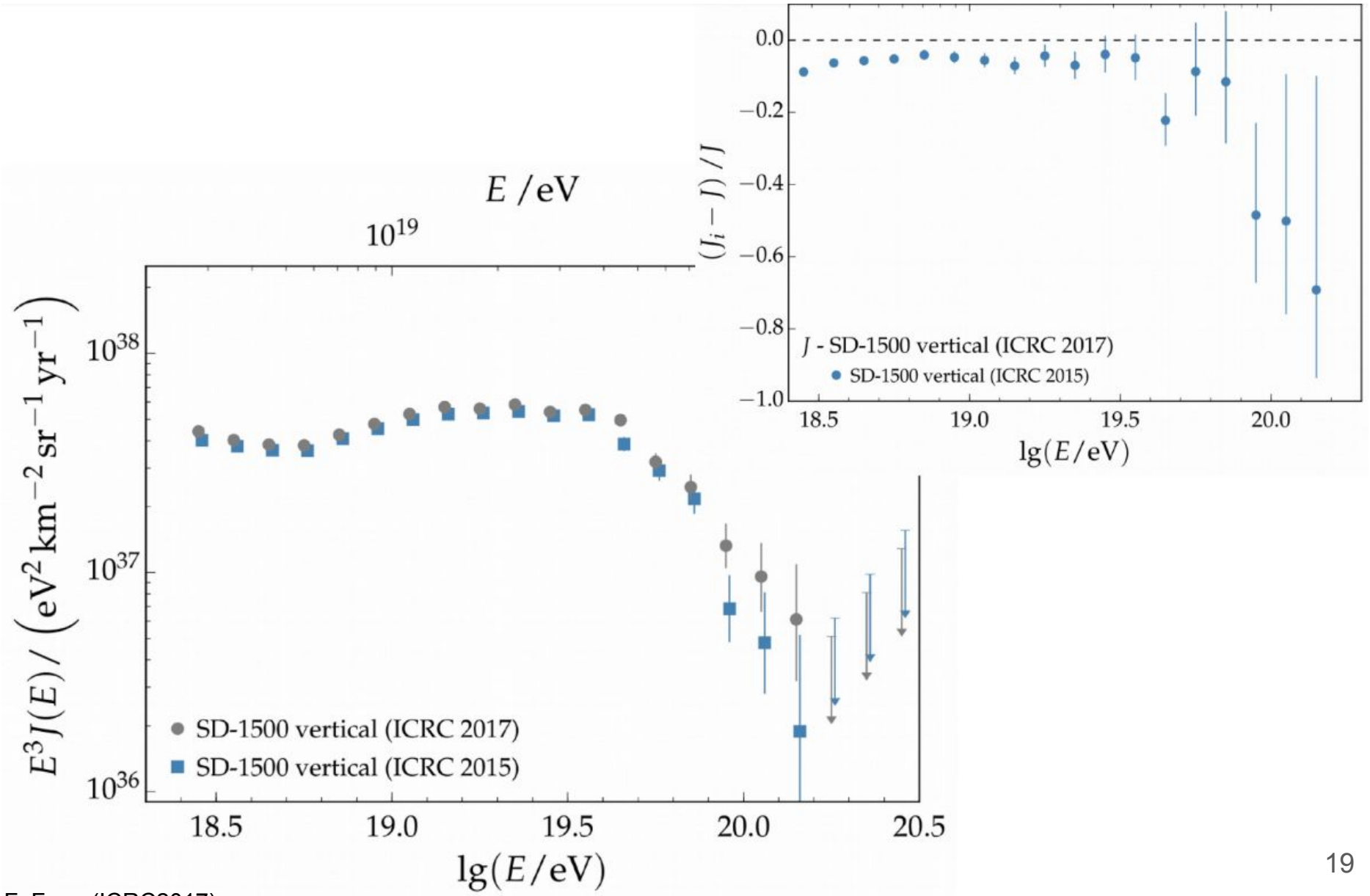
Systematic Uncertainties



Comparison with Telescope Array



New And Old Spectra



F. Fenu (ICRC2017)