

The energy spectrum of cosmic rays above 6 PeV as measured at the Pierre Auger Observatory

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Pierre Auger Observatory

An hybrid detector in the Argentinian Pampa (~1400 m a.s.l.)

Surface detector (SD)

1660 Water Cherenkov Detectors on a triangular grid with a **1500 m** spacing :

Vertical events : $\theta \leq 60^\circ$,

Inclined events : $\theta > 60^\circ$,

or **750 m** spacing :

Vertical events : $\theta \leq 40^\circ$

Duty cycle : **100%**

Fluorescence detector (FD)

24 telescopes overlooking the SD with a field of view from 0° to 30°

3 high elevation telescopes with a field of view from 30° to 60° - designed to measure lower energies

hybrid data + Cherenkov dominated events

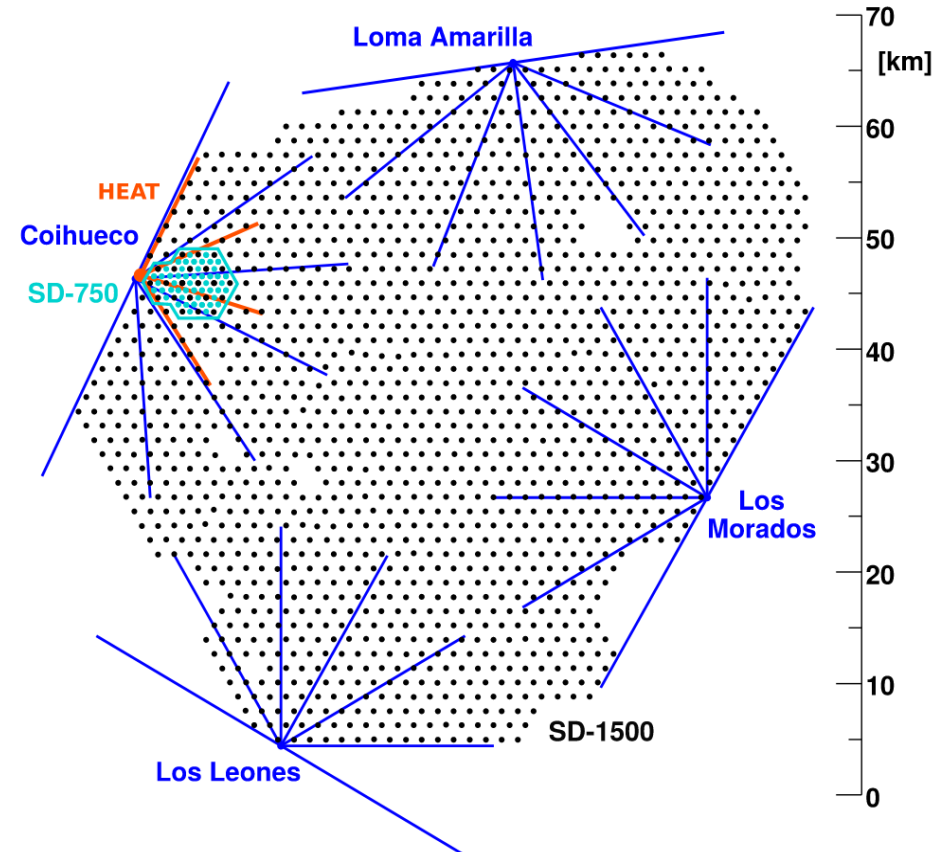
Duty cycle = **14%** (clear and moonless nights)

Radio detector, Muon counters...

Bjarni Pont's *talk*

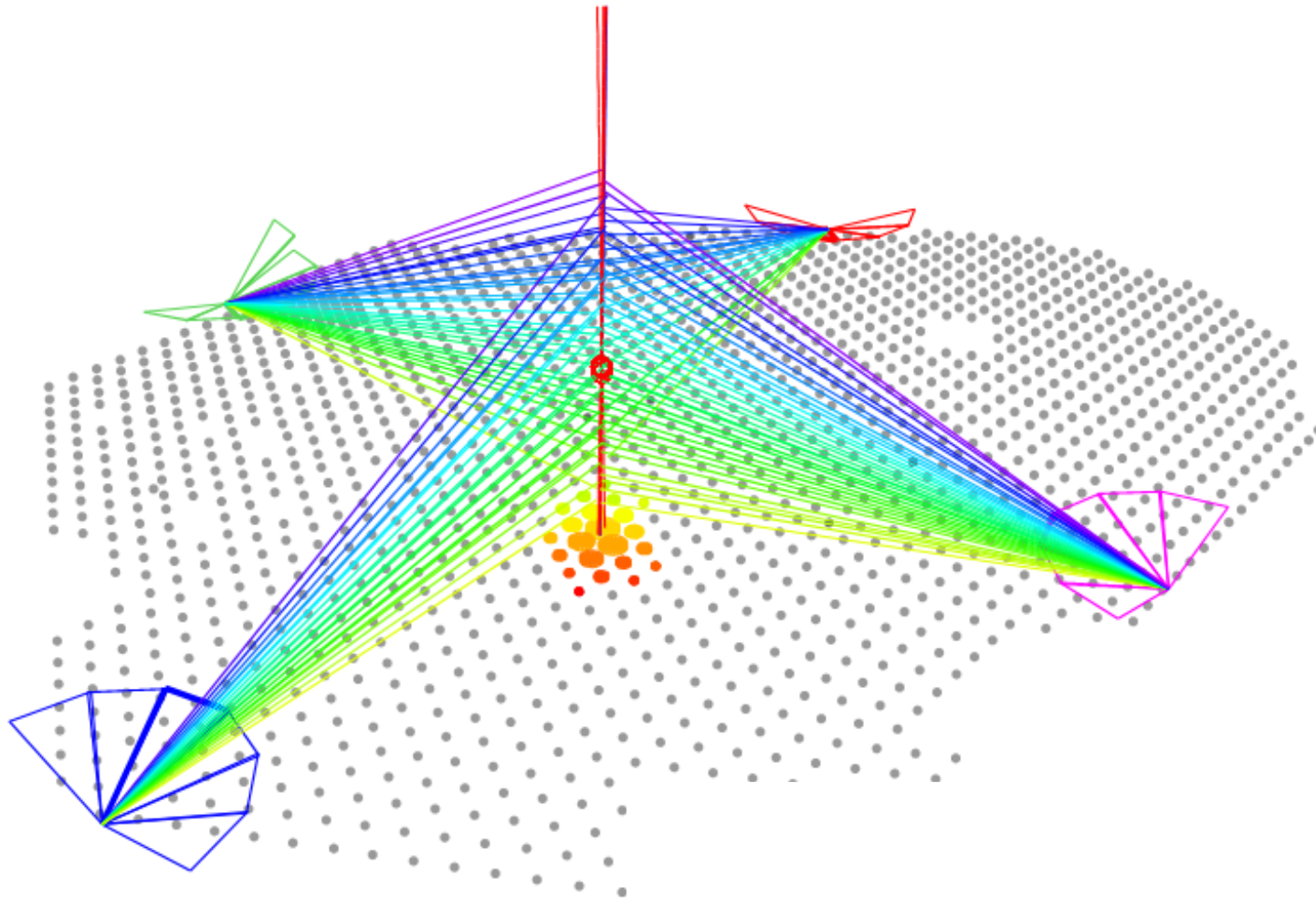
Tim Huege's *talk*

Marina Scornavacche's *poster*



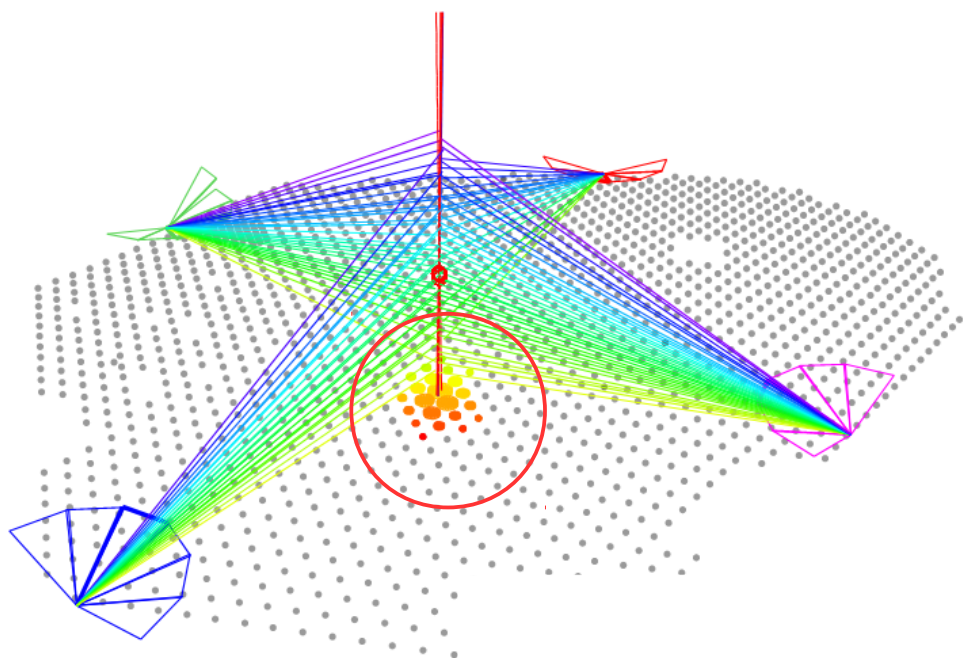
Pierre Auger Observatory

An hybrid detector in the Argentinian Pampa (~1400 m a.s.l.)



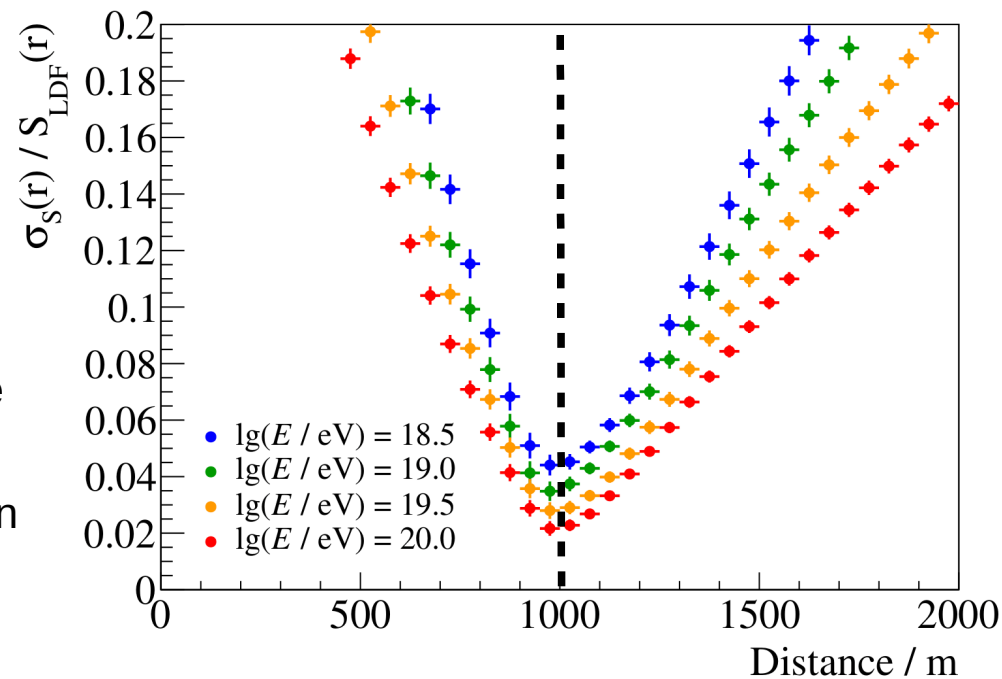
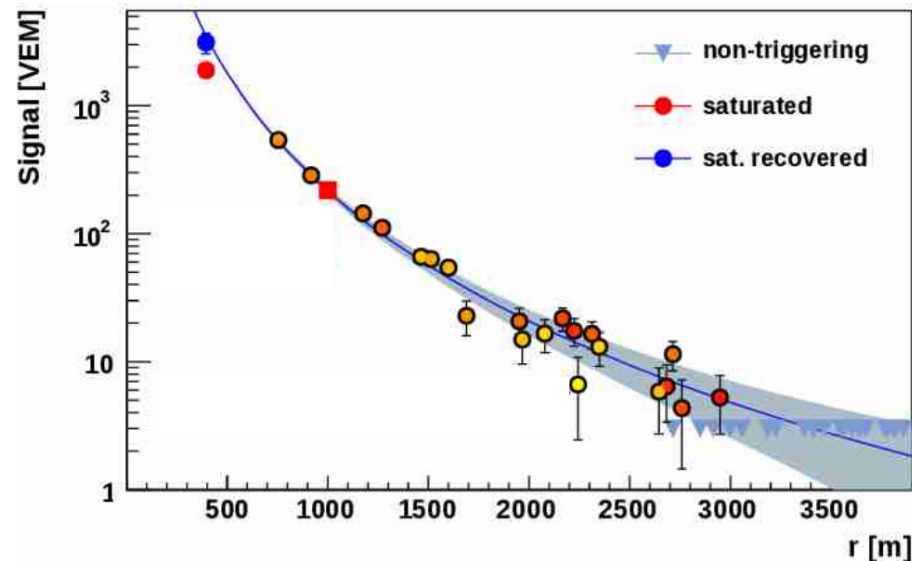
How does the Pierre Auger Collaboration reconstruct such events? How reliable is it?

Reconstruction of SD-1500m vertical events



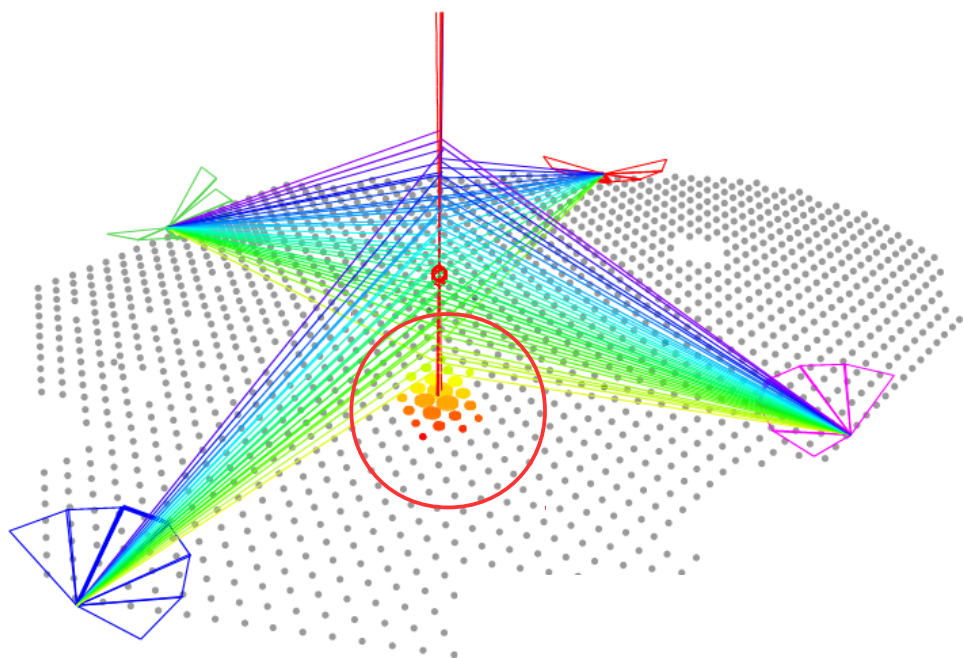
For SD-1500m array, **optimal distance to estimate the shower size is 1000 m**

See Valerio Verzi's talk for a more detailed discussion

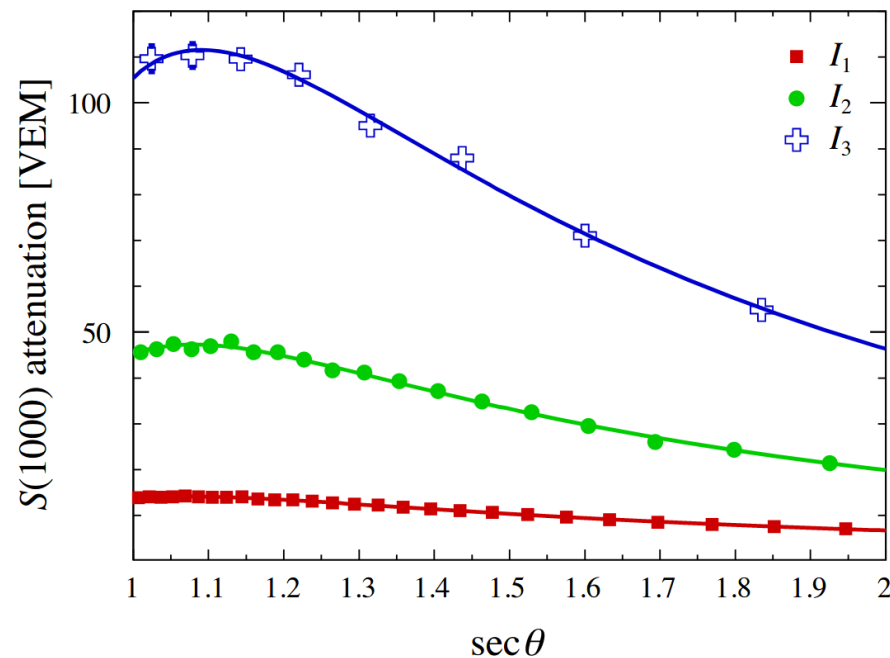
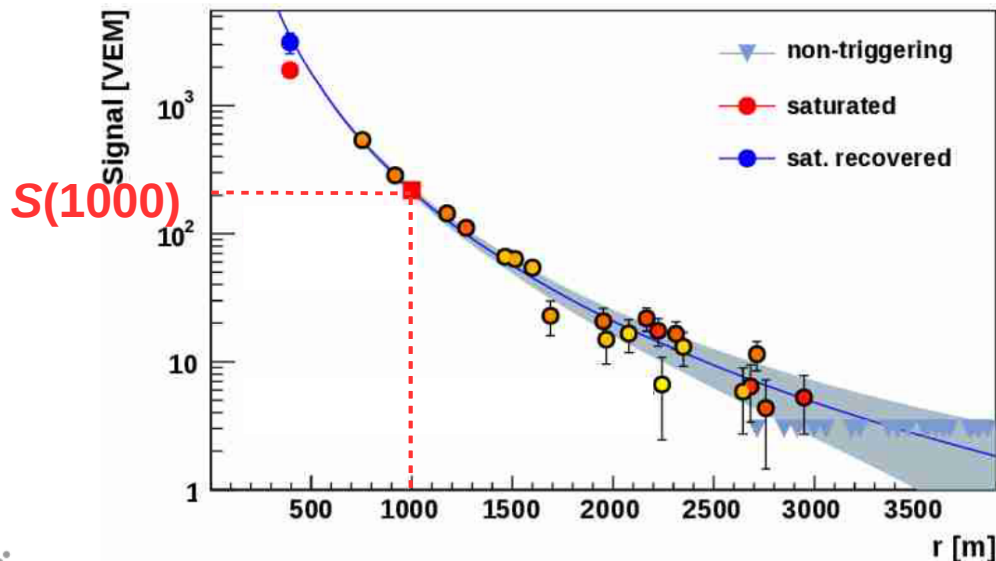


Reconstruction of SD-1500m vertical events

$S(1000)$ = signal reconstructed at 1000 m from the shower axis
 → estimator of the shower size



S_{38} = expected signal at 1000 m from a shower initiated with an inclination of 38°
 → correction of the attenuation through the atmosphere

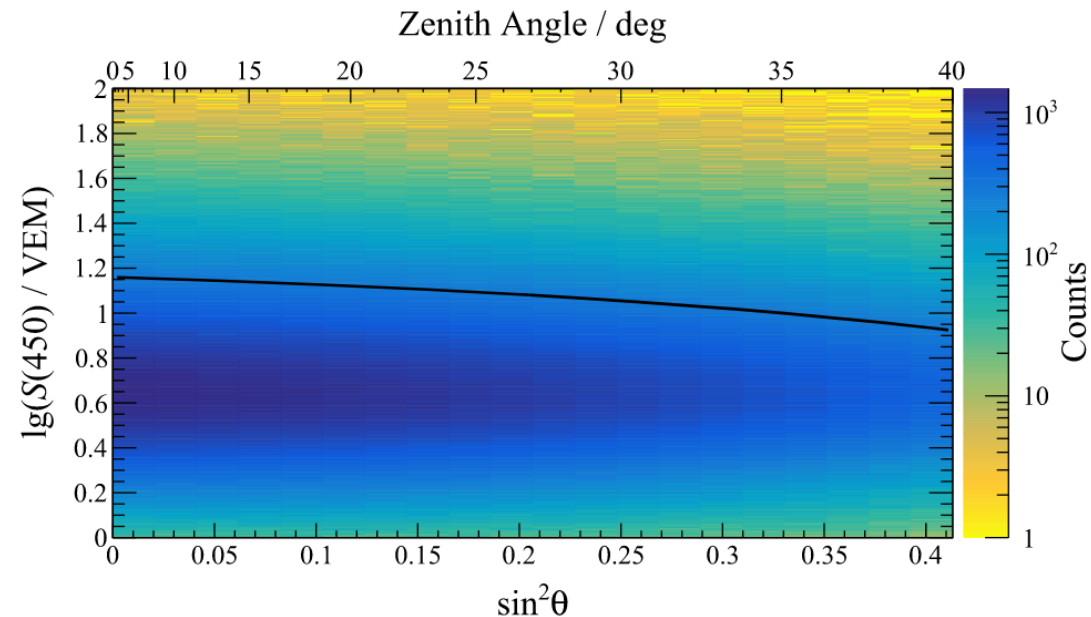
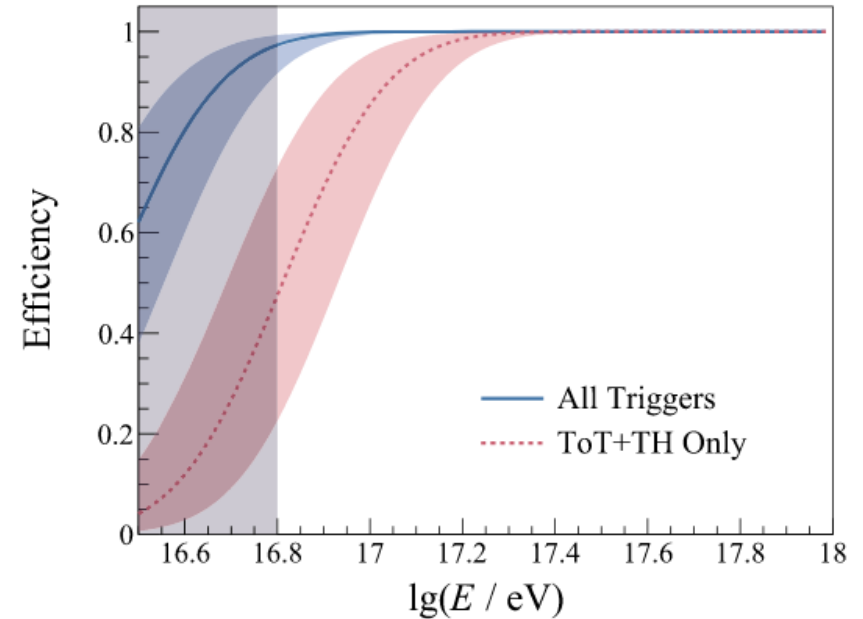


Reconstruction of SD-750m vertical events

Definition of two **new triggers** (ToTd and MoPS) to **extend the detection efficiency** to 10^{17} eV

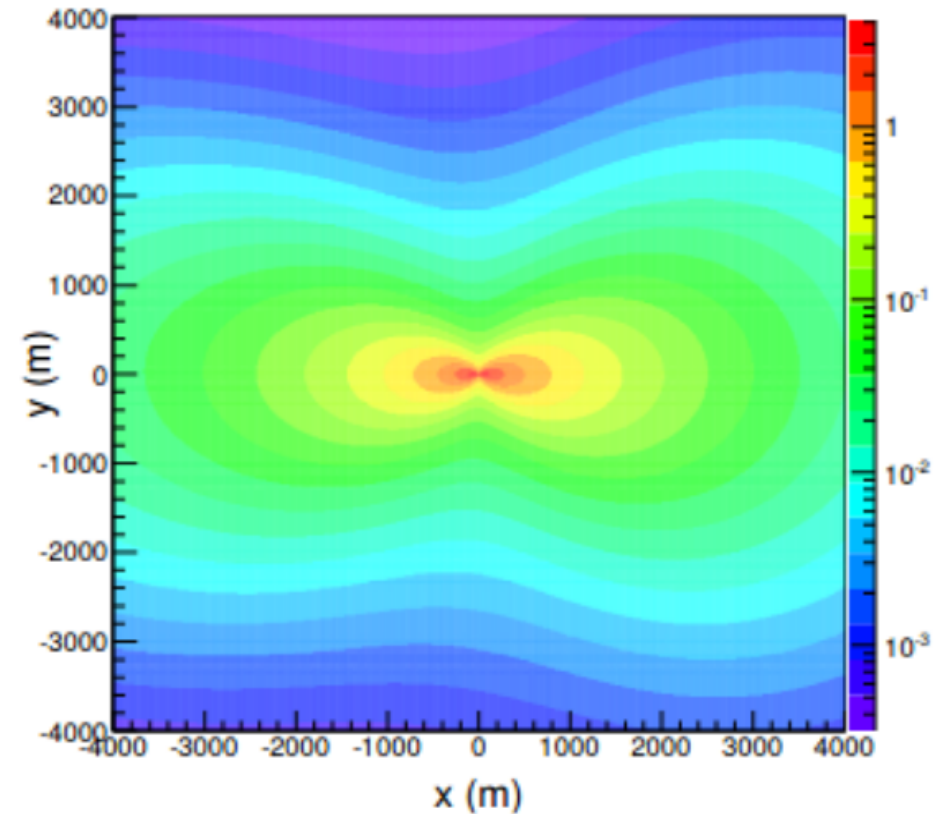
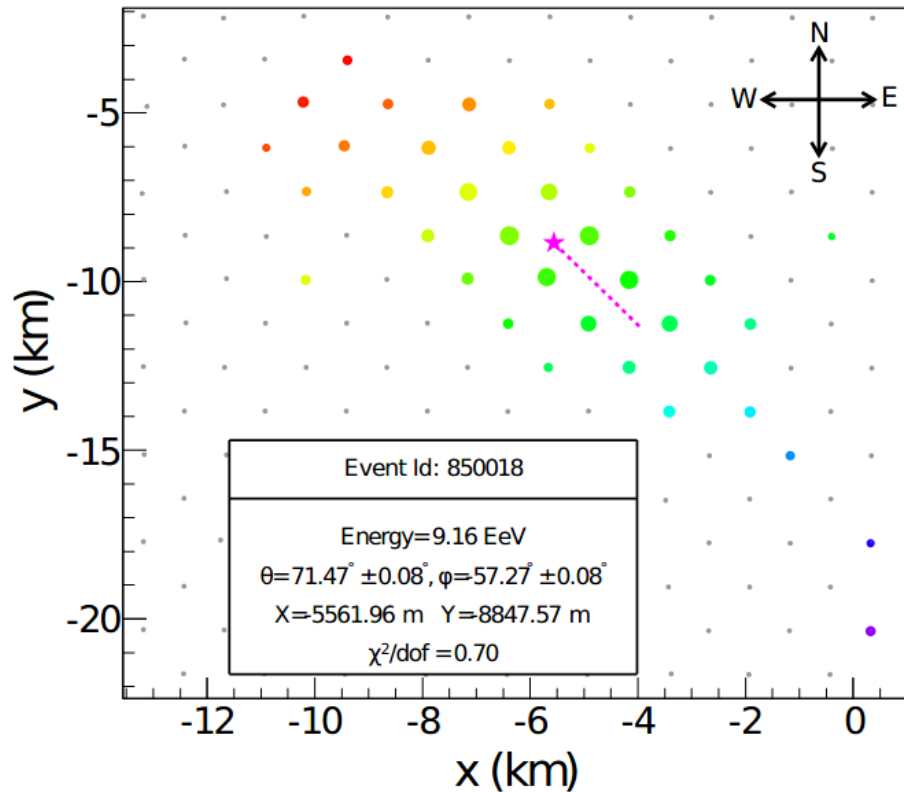
S(450) = signal *reconstructed* 450 m from the shower axis
→ **estimator of the shower size**

S₃₅ = expected signal at 450 m from a shower initiated with an inclination of 35°
→ **correction of the attenuation through the atmosphere**



Reconstruction of SD-1500m inclined events

Muon density: approximately universal for a for a given shower direction and only the **normalisation of the muon distribution density depends on the energy of the shower**



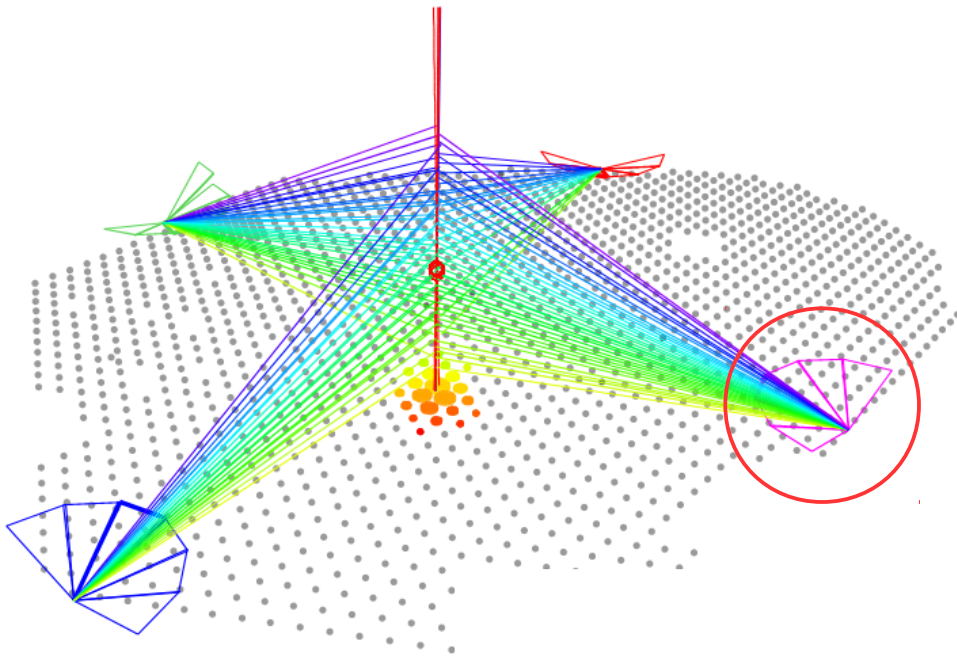
$$\rho_\mu(\vec{r}) = N_{19} \rho_{\mu,19}(\vec{r}; \theta, \phi)$$

N_{19} = measurement of the shower size

Hybrid reconstruction

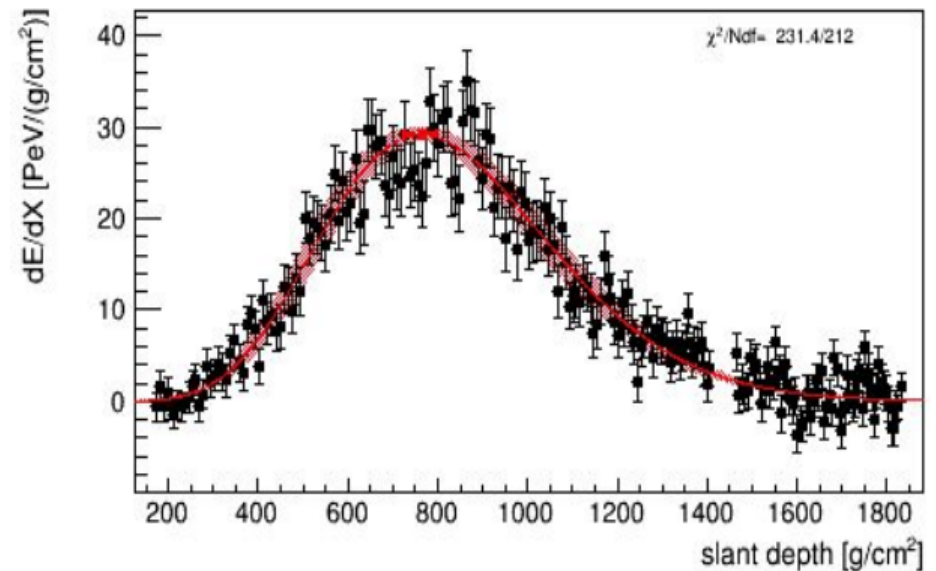
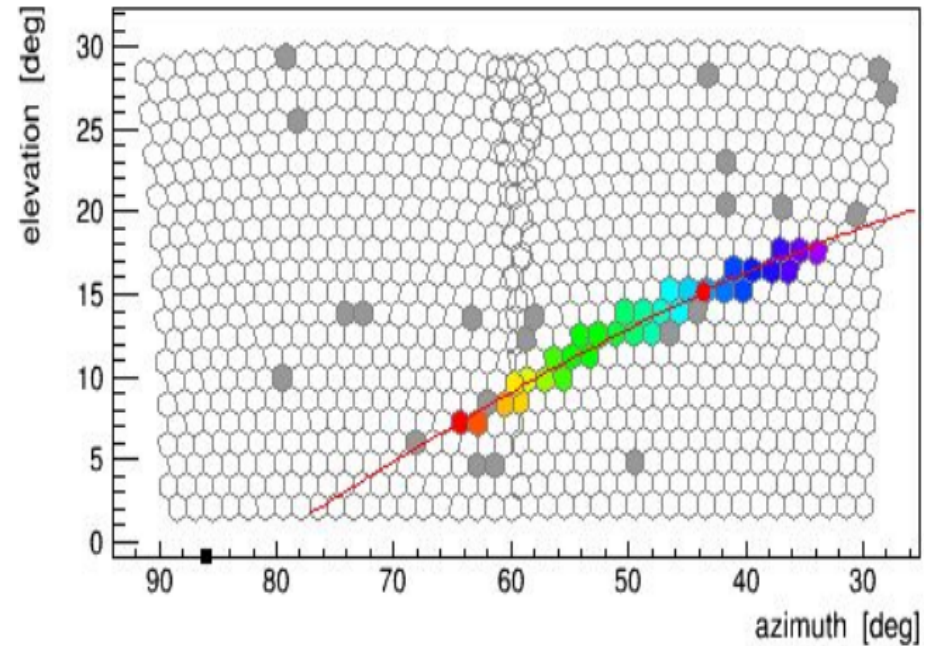
Event recorded by one of the 4 sites of telescopes
and at least 1 SD-station

Standard telescopes: $E > 10^{18.0}$ eV

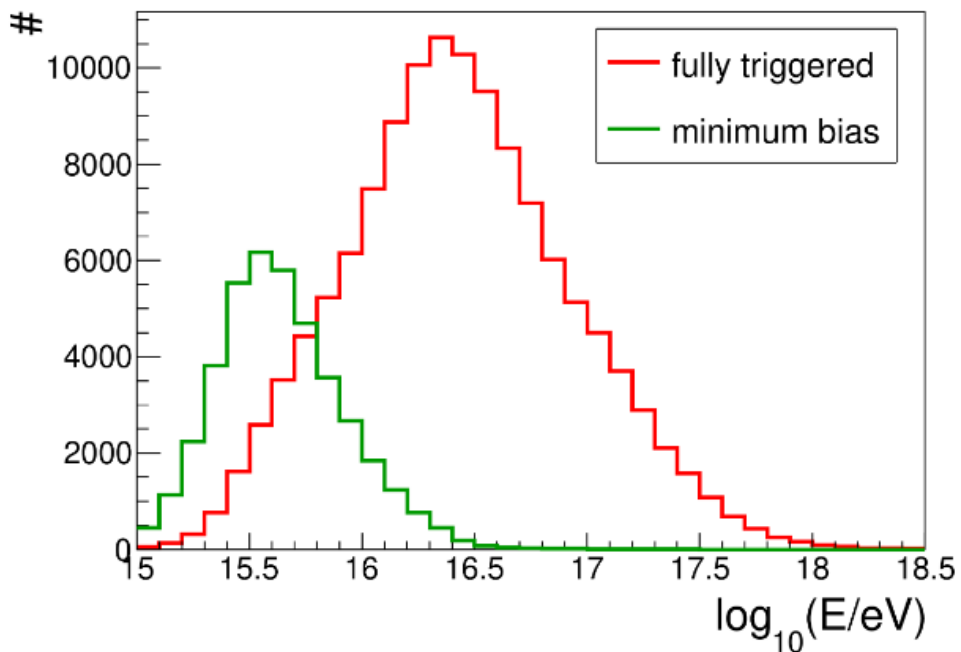
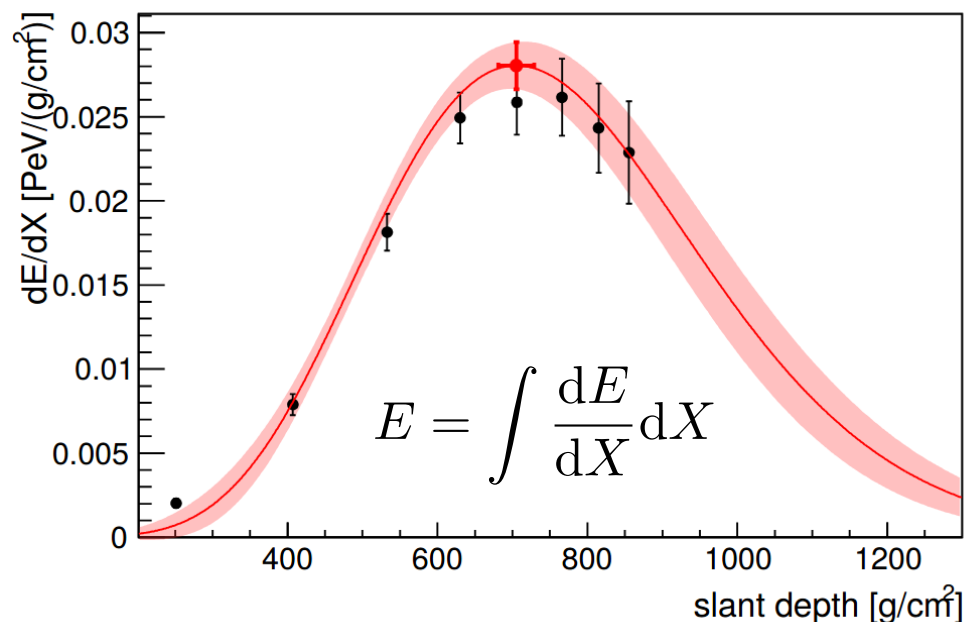
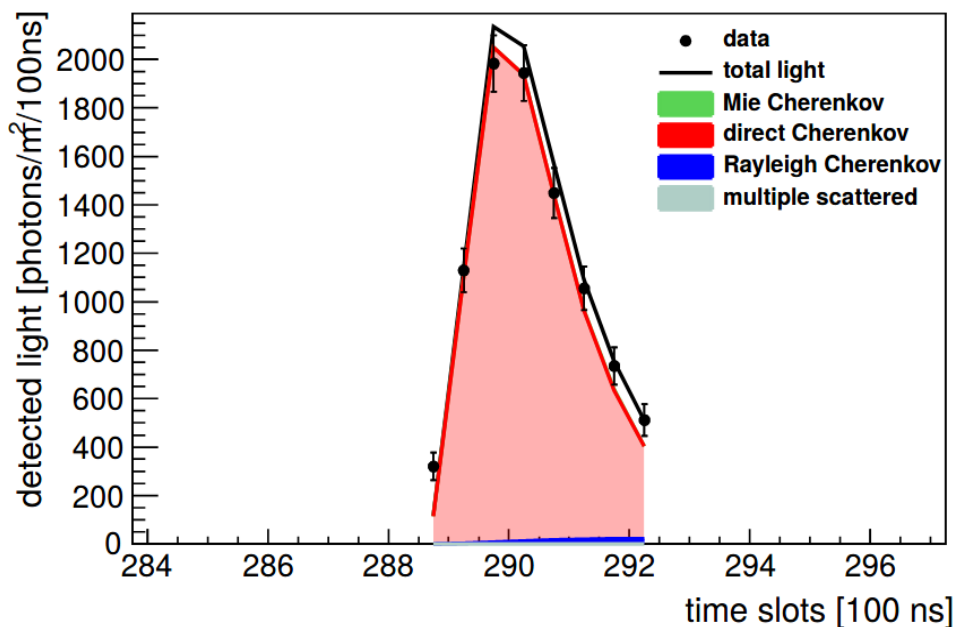


Direct measurement of the calorimetric energy:

$$E_{\text{FD}} = \int \frac{dE}{dX} dX$$



Cherenkov dominated FD-Events



HEAT + Coihueco site telescopes:

No SD counterpart at these energies, so the geometry of the shower has to be determined with a constraint on the profile

(Profile Constrained Geometry Fit)

Statistics at 6 PeV increased with minimum bias events

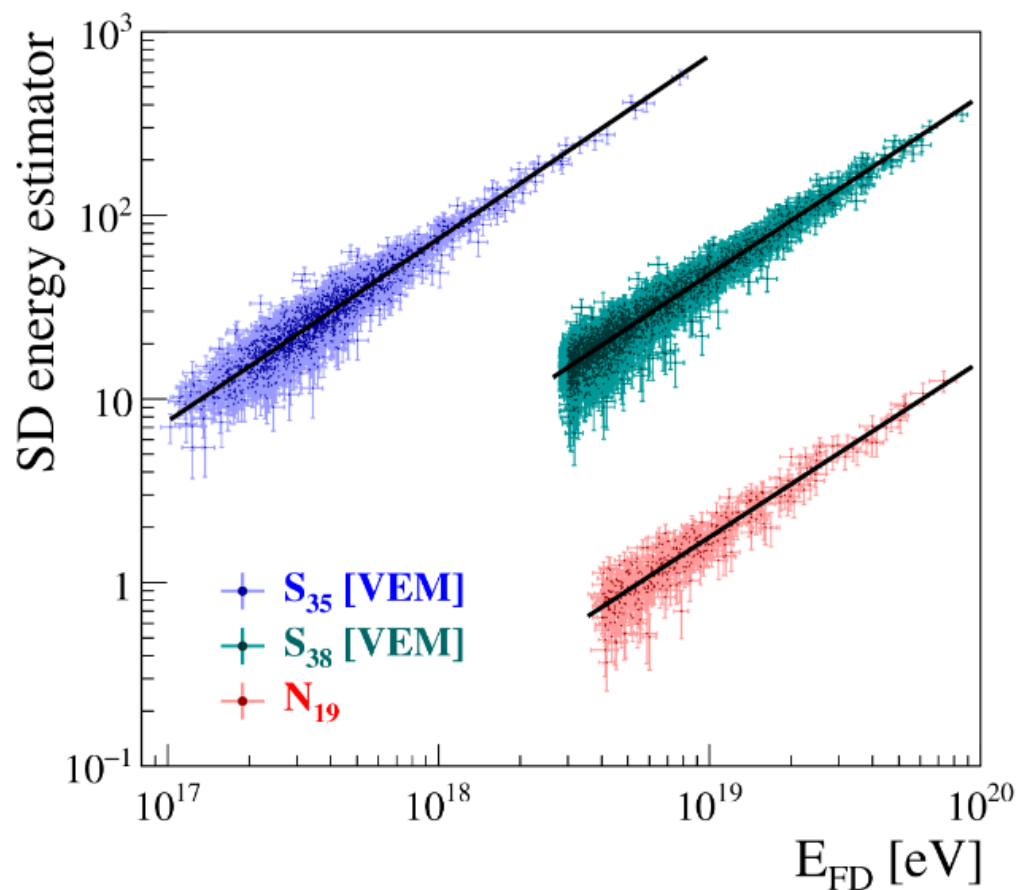
→ Events not passing the final FD trigger selection

→ 10% of them are randomly stored

SD-Calibration in energy

Estimator of the energy of the surface detector calibrated with a subset of hybrid measurements reconstructed *independently* by the SD and FD

data-driven estimation of the energy



$$E_{\text{FD}} = AS_{38}^B$$

$$E > 10^{18.4} \text{ eV}$$

$$\sigma(E) : 22\% - 7\%$$

$$E_{\text{FD}} = AS_{35}^B$$

$$E > 10^{17} \text{ eV}$$

$$\sigma(E) : 25\% - 10\%$$

$$E_{\text{FD}} = AN_{19}^B$$

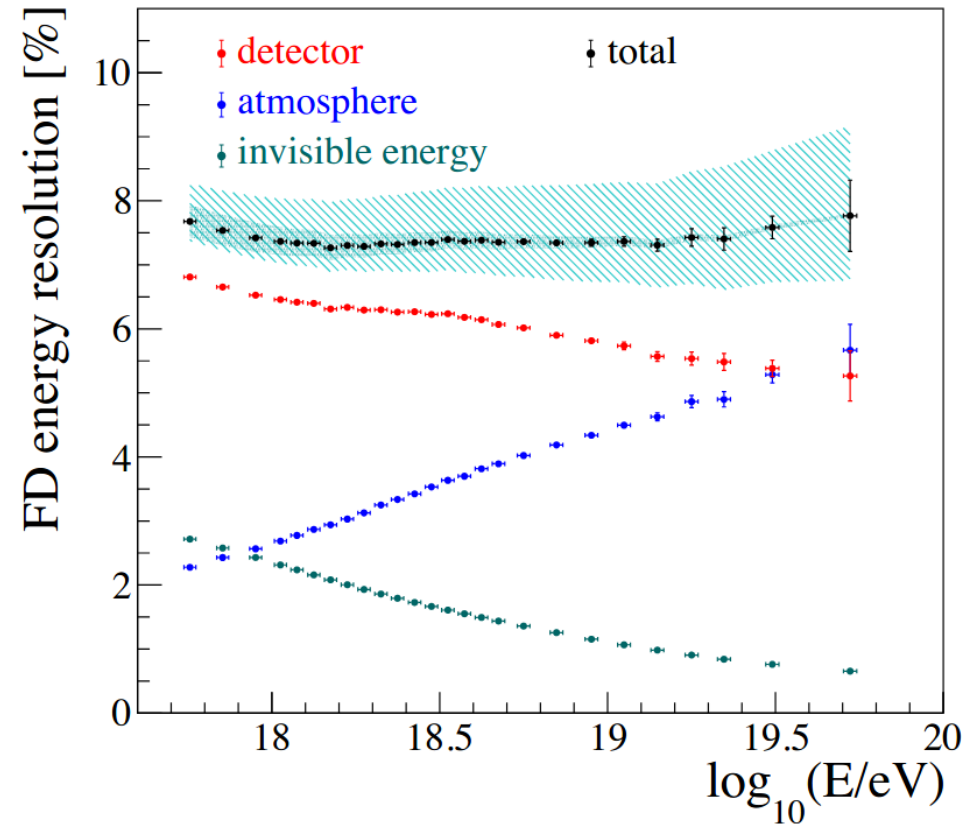
$$E > 10^{18.6} \text{ eV}$$

$$\sigma(E) \sim 19\%$$

Energy scale and energy resolution

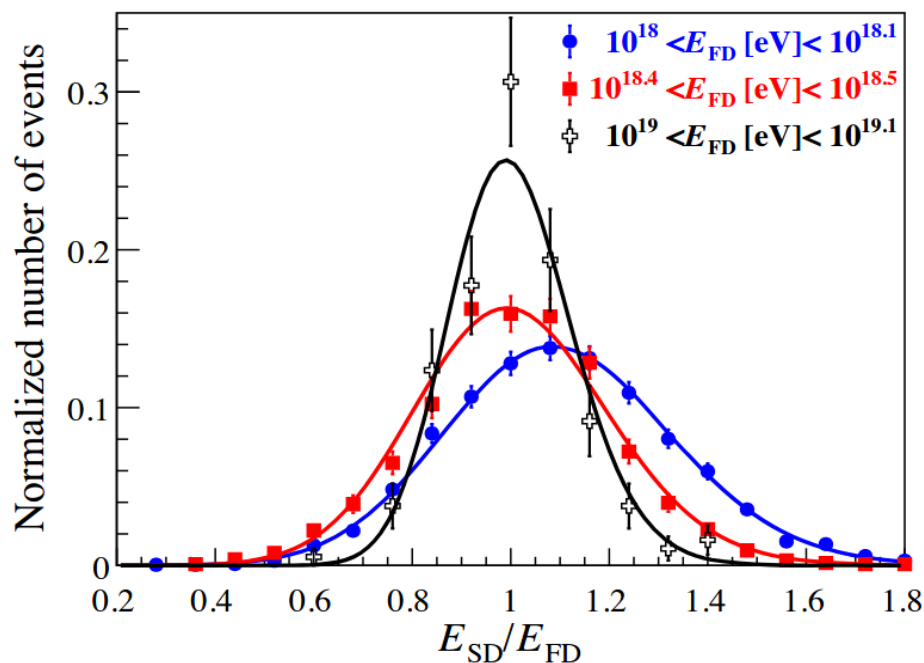
Both **energy scale** and **energy resolution** of the Pierre Auger Observatory are obtained using hybrid events

Systematic uncert. in energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Energy scale stability	5%
TOTAL	14%

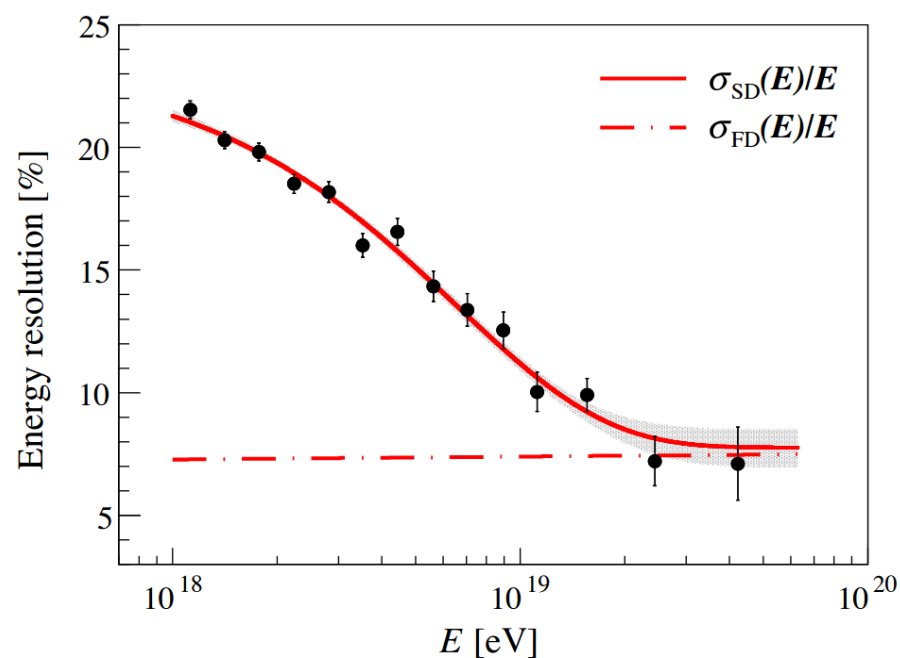
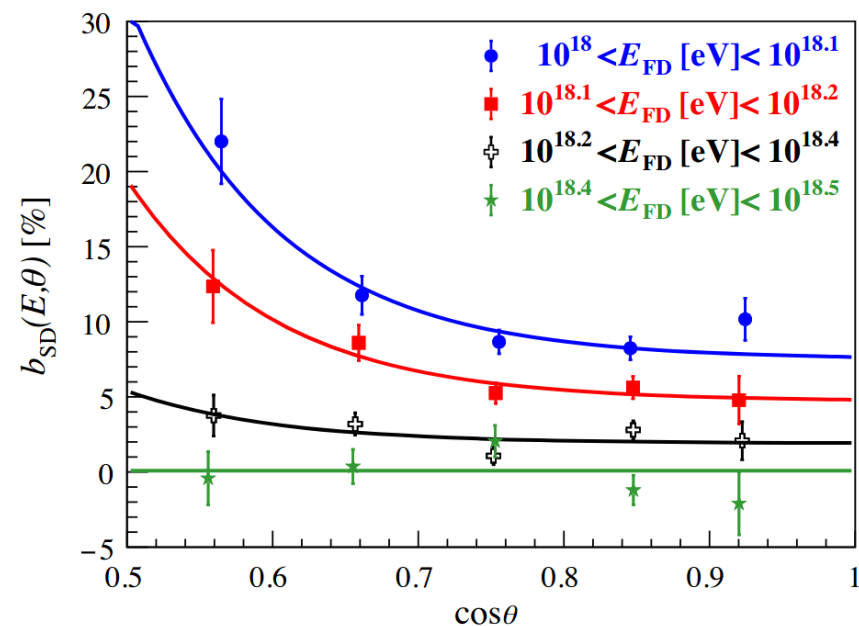


SD-1500m, energy systematics

Bias and resolution estimated considering the distribution of E_{SD} / E_{FD}



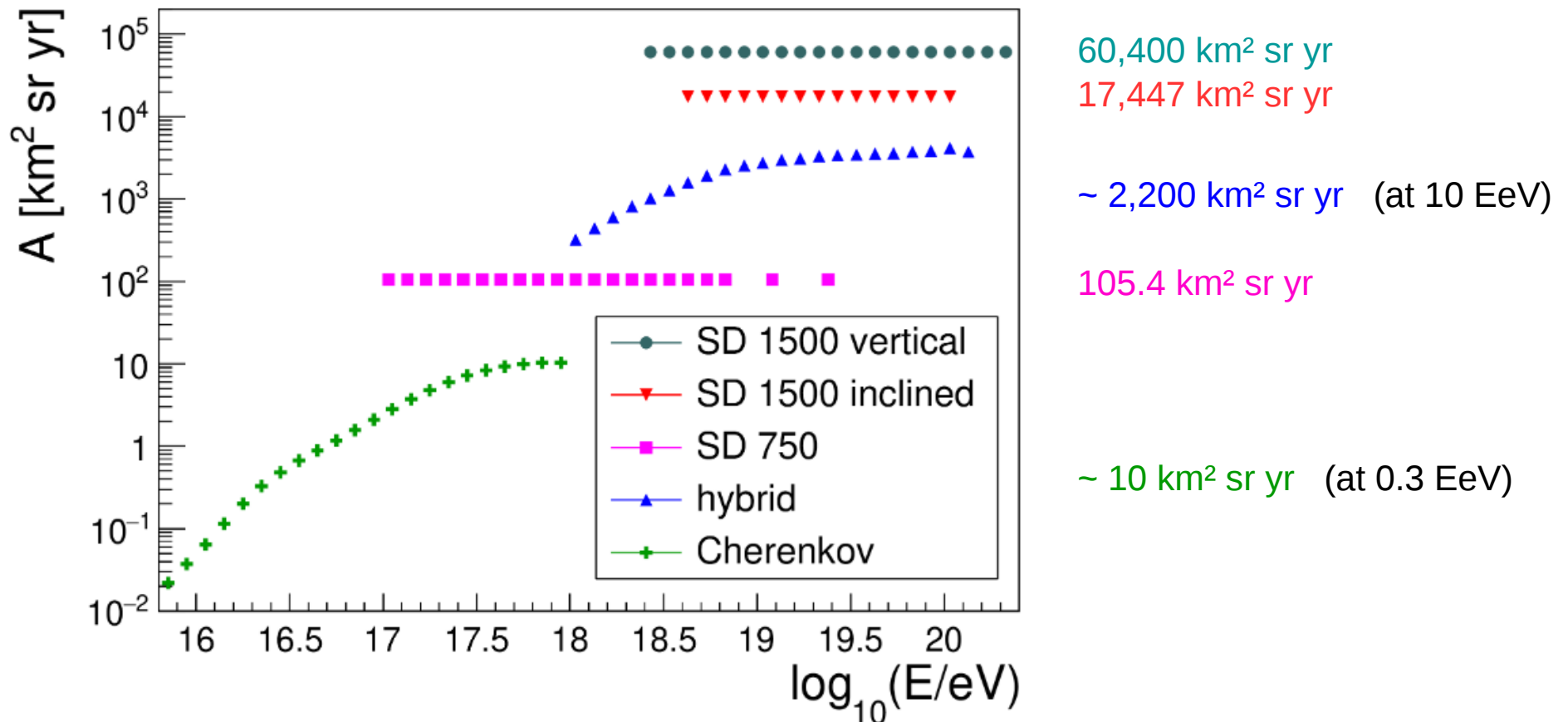
Same procedure applied for all SD data-sets



Exposure of the detectors

Surface Detectors: above energy threshold, it reduces to a geometrical problem
→ count of **active hexagon cells** and **independent of energy**

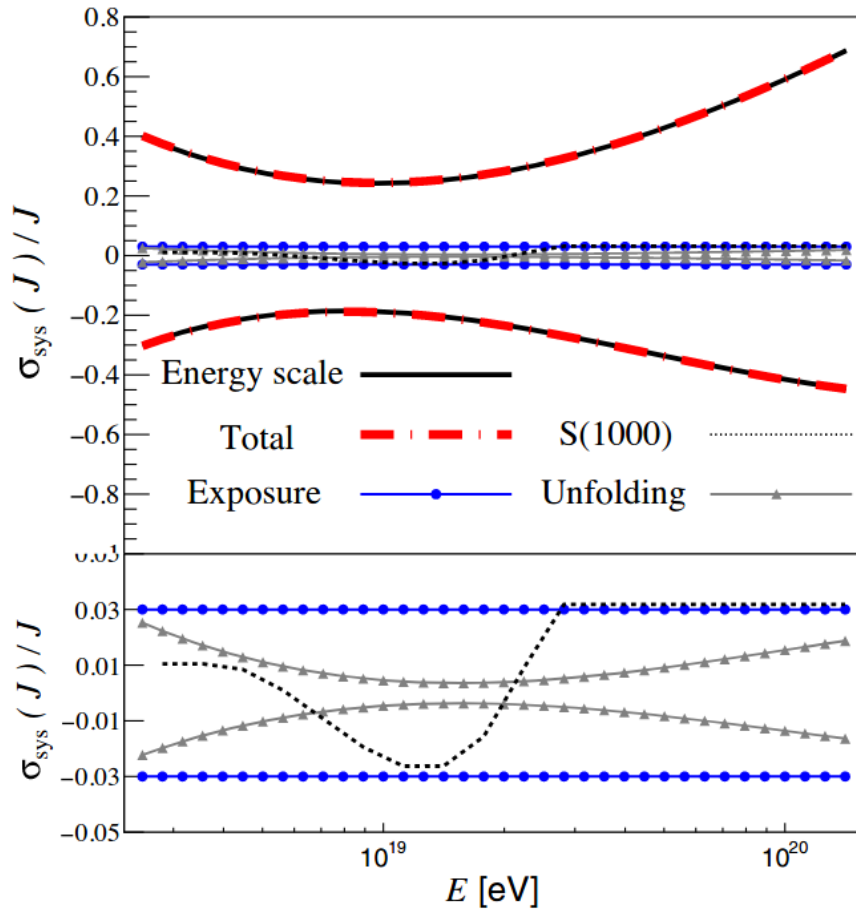
Fluorescence Detectors: exposure from detailed MC simulation of FD events including the status of atmosphere and detector → **increase with energy**



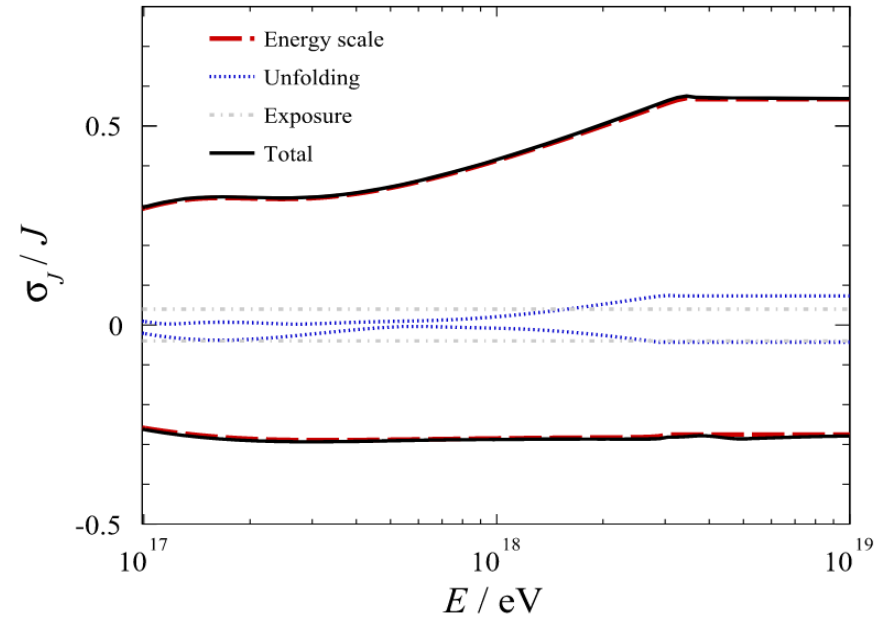
Spectrum systematics

Systematics dominated by the **uncertainties on the energy scale** (except at the lowest energies for the Cherenkov spectrum)

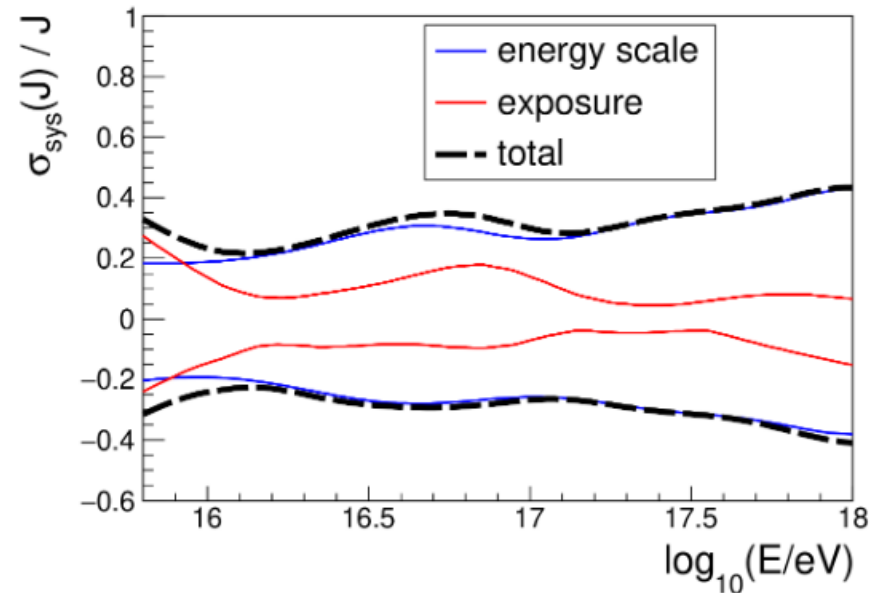
SD-1500m



SD-750m



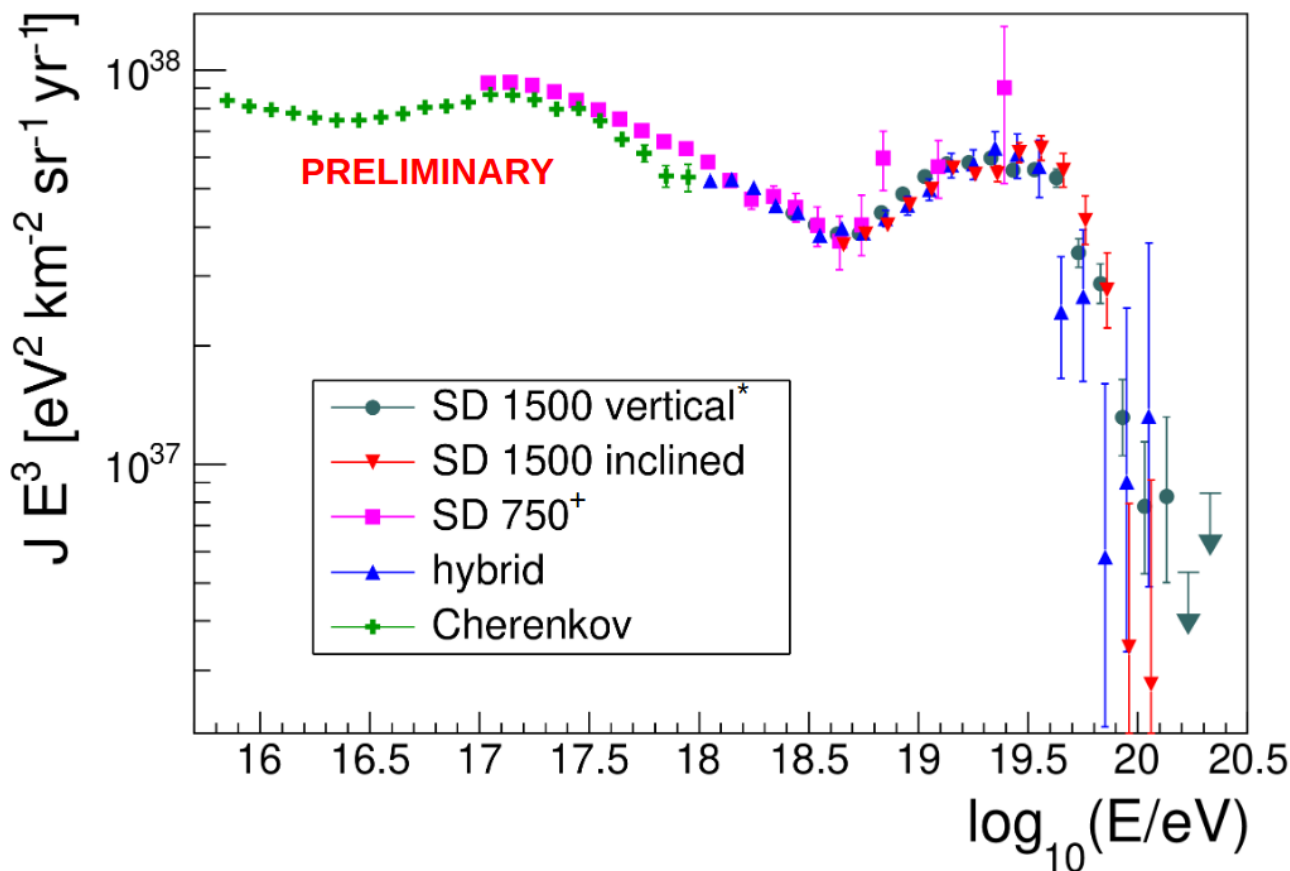
Cherenkov spectrum



5 data-sets, 5 spectra

Unfolding procedure applied to account for the detector effects

Energy spectra **consistent within the systematic uncertainties** after rescaling

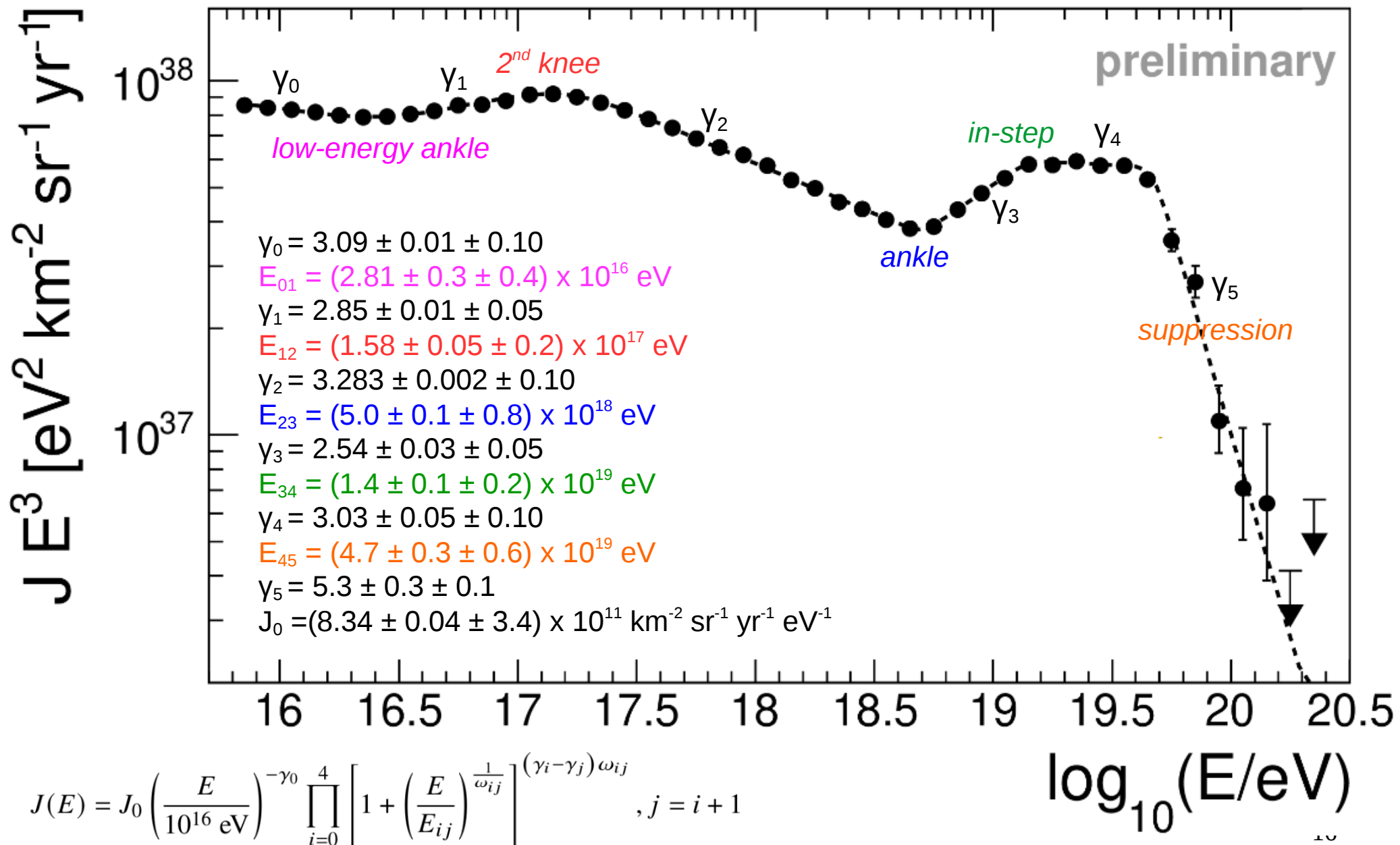


Normalisation shifts after combination of all spectra:

- <1% SD-1500 m vertical
- +5% SD-1500 m inclined
- 2% SD-750 m
- <1% Hybrid
- +7% Cherenkov

Combination performed considering, for each data-sets, **adjustable shifts in exposure and energy within uncorrelated uncertainties**

Combined spectrum



A glimpse into the (near?) future

A denser array: **SD-433 m**

→ **$E > 50$ PeV** ($\theta < 45^\circ$)

→ reinforcements of the measurements of the **second knee** with a **6th spectrum**

G. Silli (2021), *PoS(ICRC2021)224*

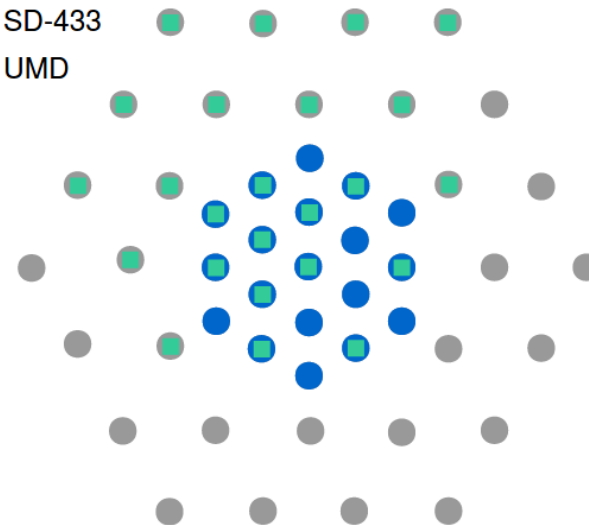
Upgrade of SD (addition of scintillators on top of the WCD) + muon detectors:

→ spectrum for different mass primaries

● SD-750

● SD-433

■ UMD

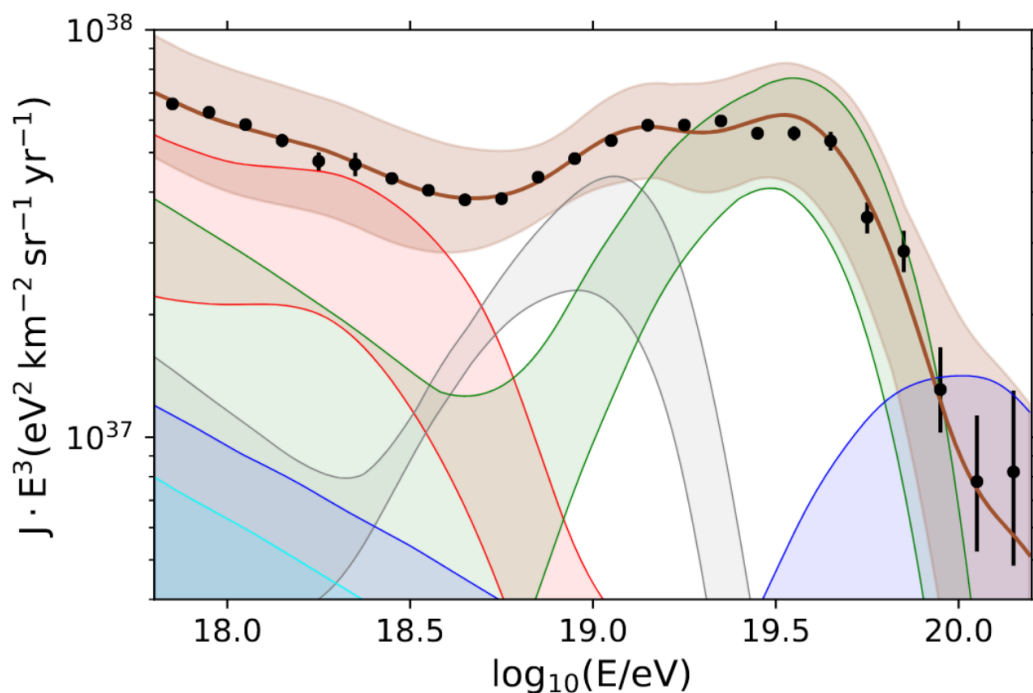


Interpretation of the observed spectral features using the **mass composition data**

Eleonora Guido's *talk*

+ **arrival direction data**

Teresa Bister's *talk*



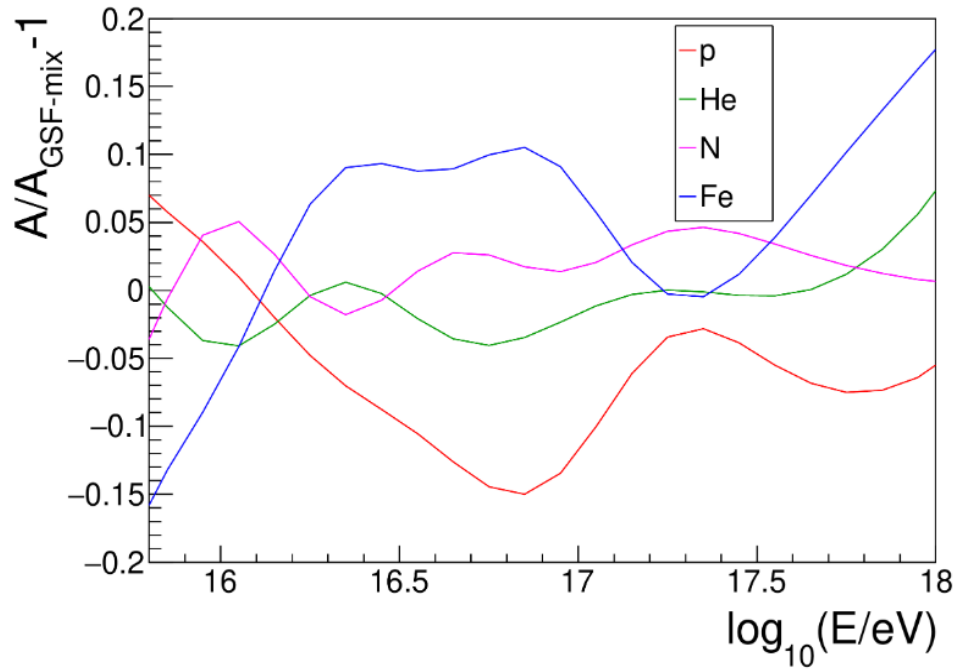
Trugarez !*

* Thank you!

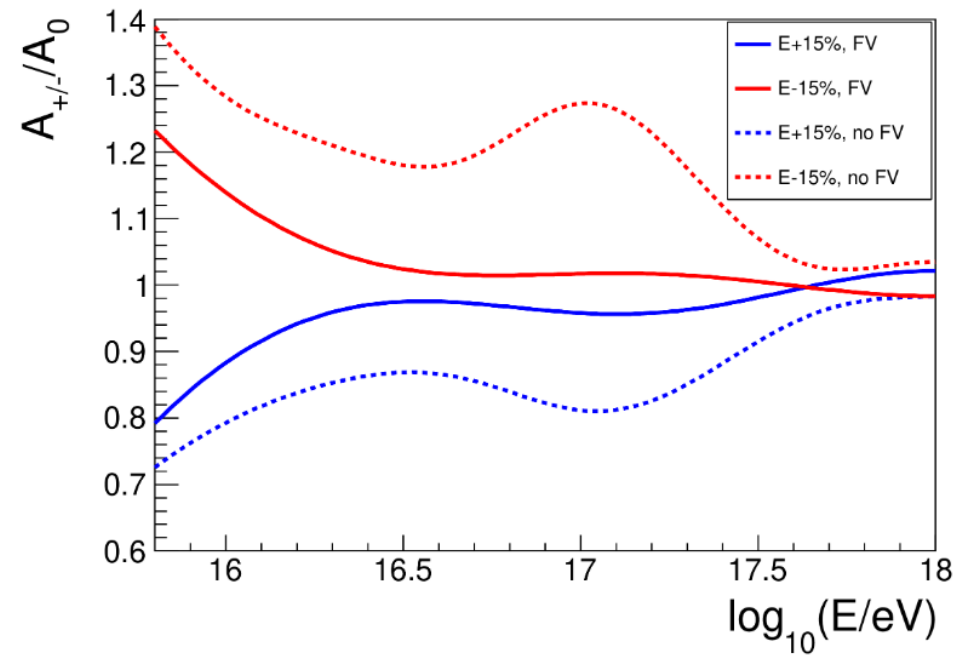
Back-up

Exposure of Cherenkov dominated FD-Events

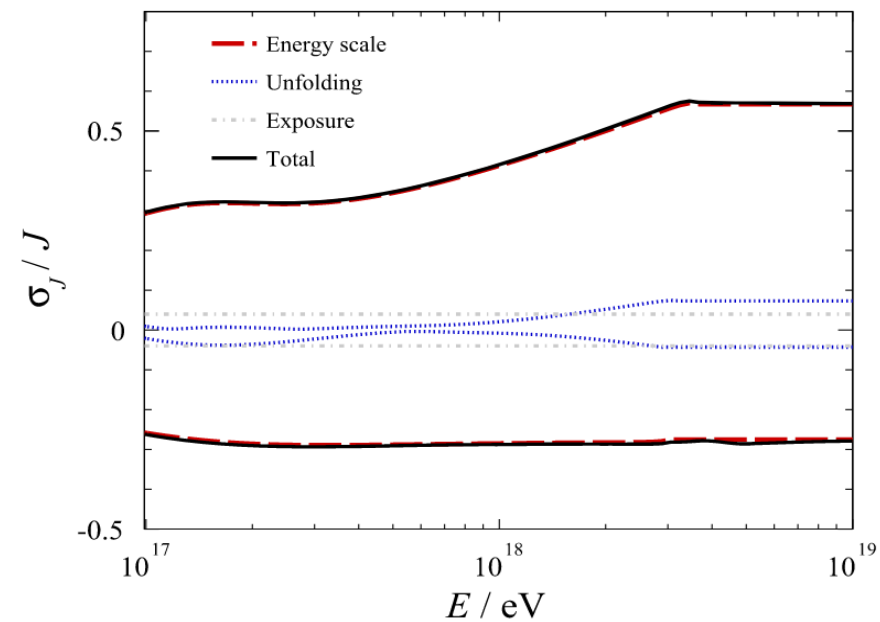
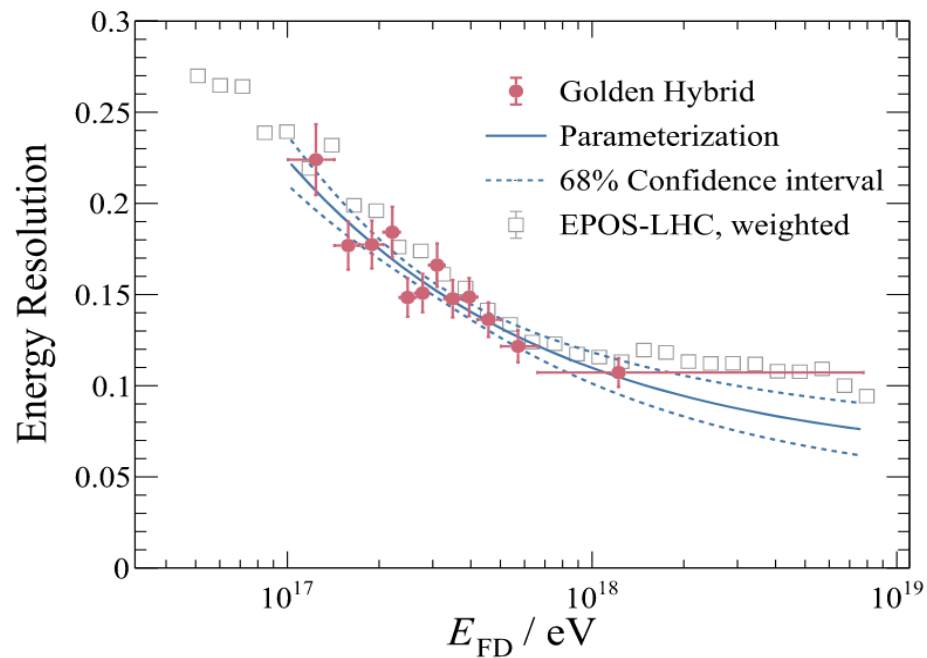
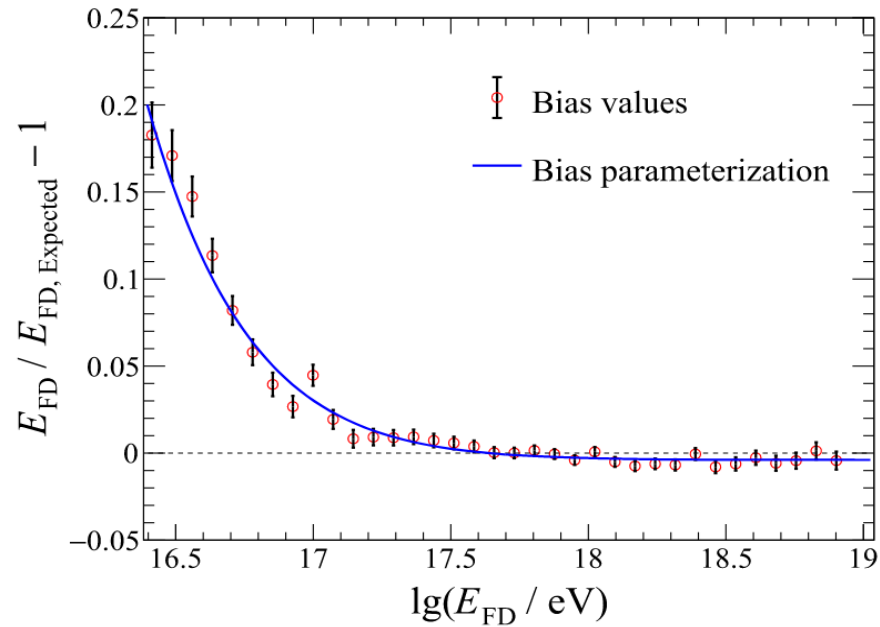
Mass composition uncertainties:



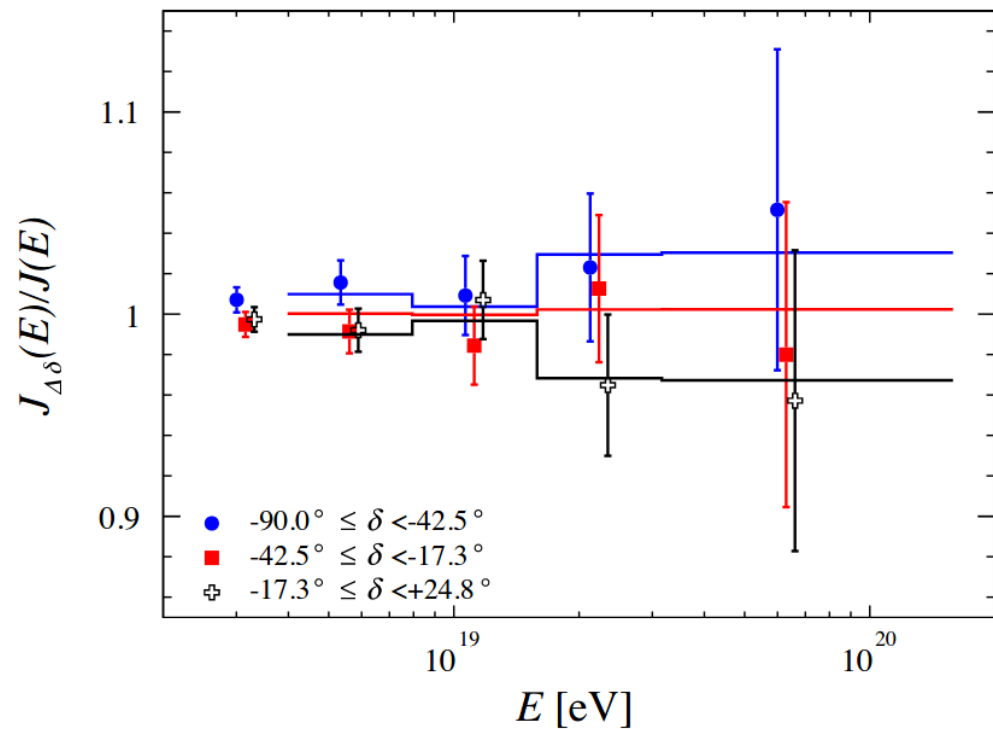
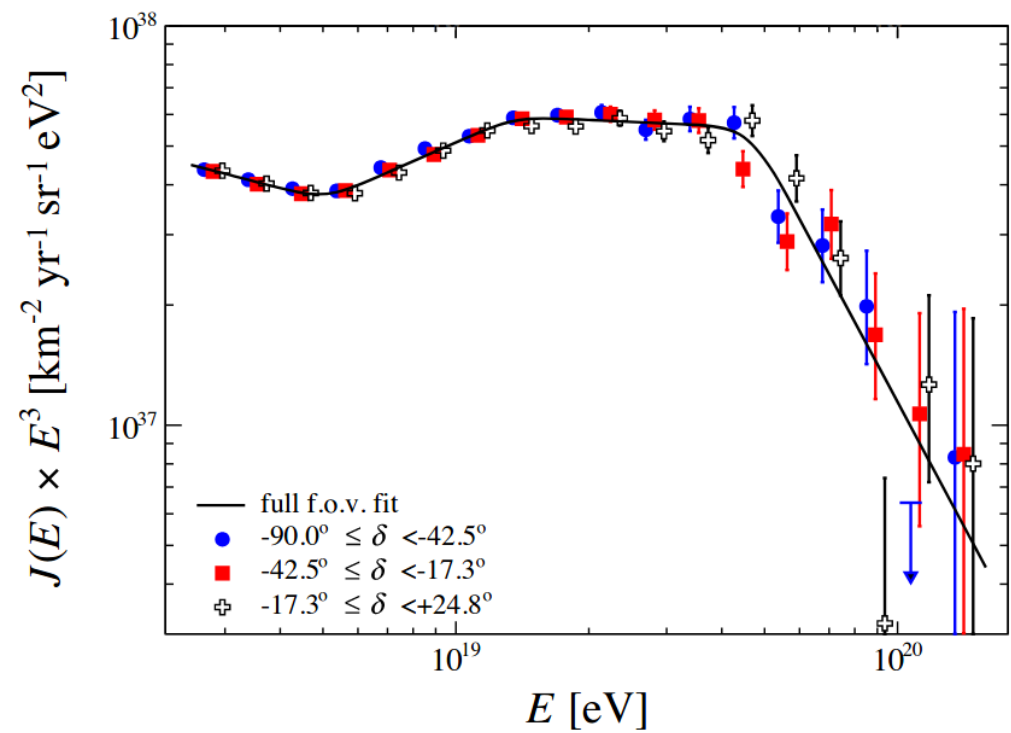
Fiducial volume cuts on shower geometry:



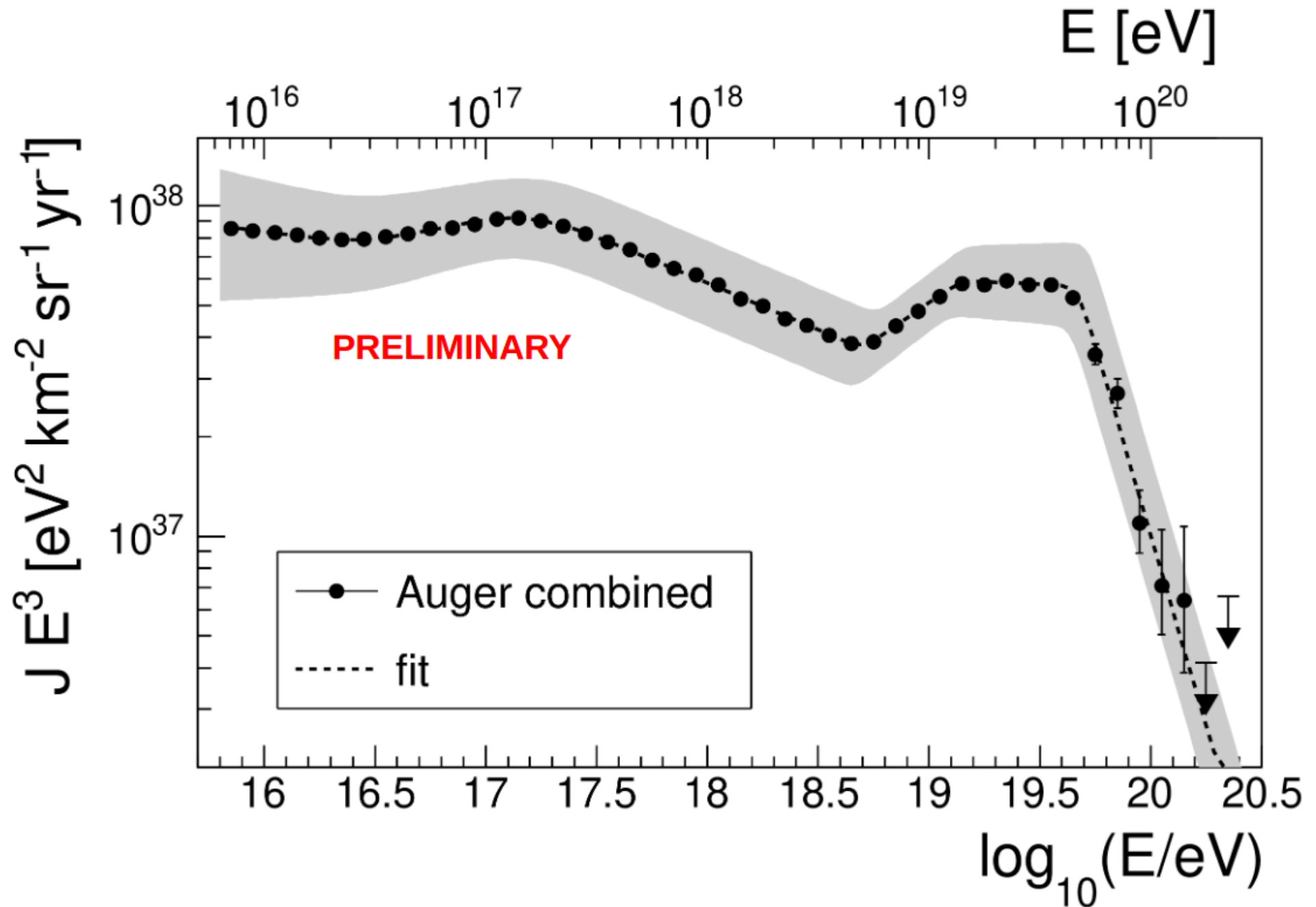
SD-750m, spectrum systematics



SD-1500m, declination dependency



Systematics uncertainties on combined spectrum



Comparison with other experiments

