Measuring the spectrum of UHECR with the Pierre Auger Observatory

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III RICAP

Outline

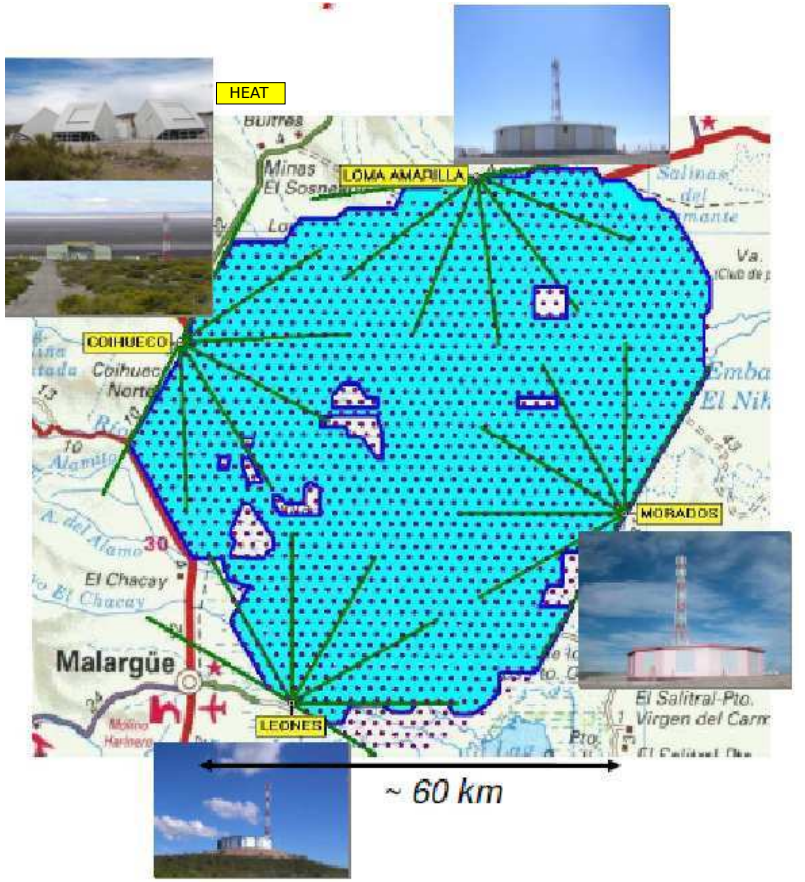
- Pierre Auger Observatory
- Hybrid Data Analysis and Spectrum
  - On-time Calculation
  - Time Dependent Monte Carlo Simulation
  - Event Selection
  - Hybrid Exposure
  - Hybrid Spectrum
- Surface Detector Exposure and Spectrum
- Combined Spectrum
- Conclusions

Pierre Auger Observatory

(see also Carla Bonifazi's talk)

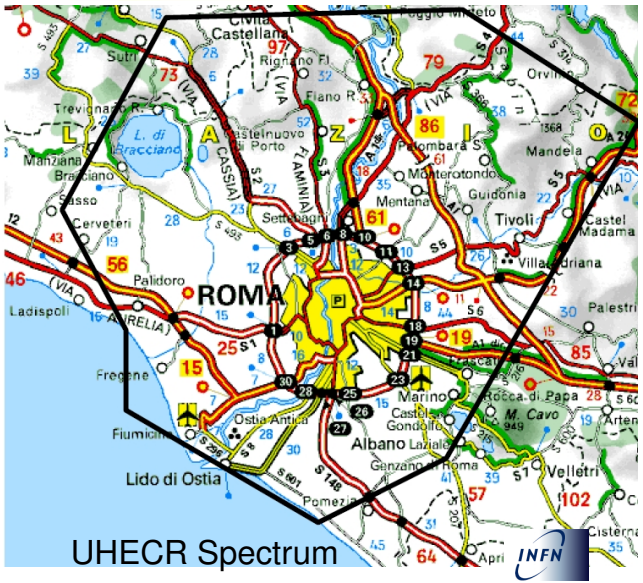
Surface Detector (SD)

- 1660 water Cherenkov detectors
- 1.5 km spaced (3000 km^2 area)
- 100% duty cycle



Fluorescence Detector (FD)

- 4+1 Fluorescence sites
- 6(3) telescopes per site (30° FoV)
- 13% duty cycle



UHECR Spectrum

UHECR Spectrum

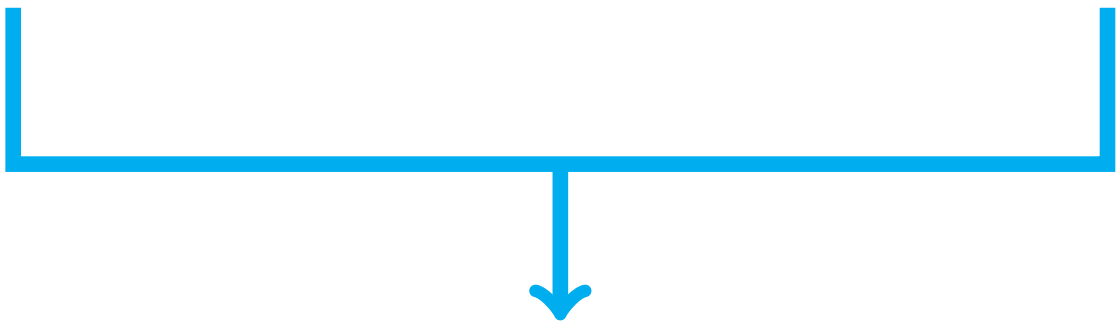
Different detectors $\Rightarrow$ different data $\Rightarrow$ distinct spectra

FD+SD $\Rightarrow$ **HYBRID SPECTRUM**

- $E \gtrsim 10^{18}$ eV
- lower exposure
- ankle region

SD only $\Rightarrow$ **SD SPECTRUM**

- $E \gtrsim 10^{18.5}$ eV
- higher exposure
- trans-GZK region



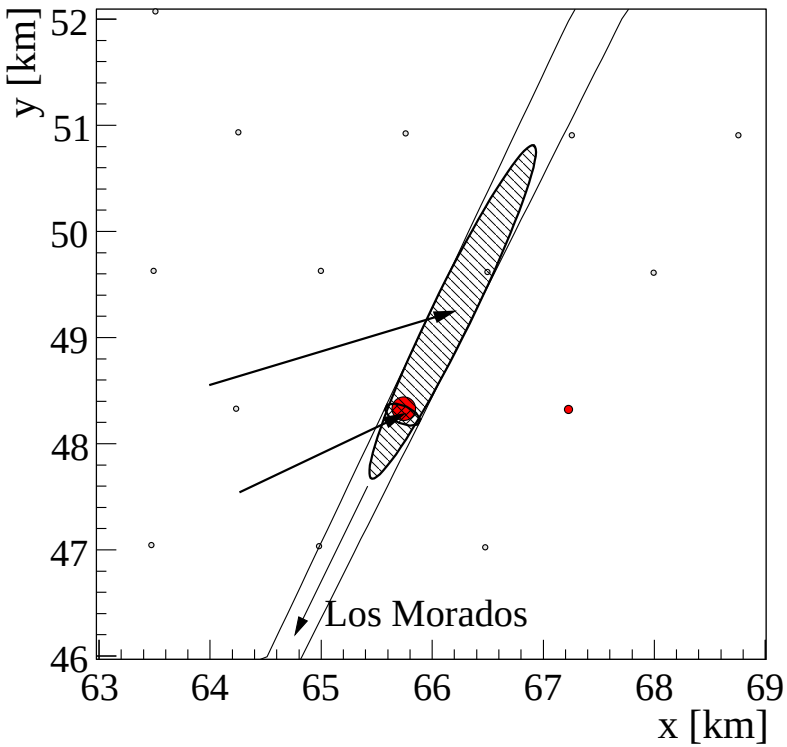
COMBINED SPECTRUM

Hybrid Data Analysis

BRASS HYBRID EVENTS i.e FD event + 1 SD station

Benefits

- increase statistics w.r.t *golden hybrid* events (reconstructed with both FD and SD);
- extend the spectrum below SD threshold ($10^{18.5}$ eV $\rightarrow\sim 10^{18}$ eV);
- improve geometrical reconstruction (0.6° angular res. and 50 m core location)
- improve energy reconstruction (10% resolution)



Cosmic Ray Spectrum with Hybrid Events

Spectrum

$$J(E) = \frac{\mathrm{d}N}{\mathrm{d}E\mathrm{d}A\mathrm{d}t\mathrm{d}\Omega} \simeq \frac{\Delta N_{\mathrm{sel}}(E)}{\Delta E}\frac{1}{\mathcal{E}(E)}$$

Exposure

$$\mathcal{E}(E) = \int_T \int_\Omega \int_S \varepsilon(E,t,\theta,\phi,x,y)\ \cos\theta\ \mathrm{d}S\ \mathrm{d}\Omega\ \mathrm{d}t = \int_T \mathcal{A}(E,t)\ \mathrm{d}t$$

Configurations changing over the time

- SD stations (deployment, status, ...)
- FD telescopes (construction, optical configurations, DAQ failures, ...)
- Atmospheric conditions

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The Method

Take into account all the detector configurations and their time variability simulating a sample of events which exactly reproduces the experimental conditions

$$\mathcal{E}(E_{\mathrm{rec}}) = 2\pi\ \mathrm{S_{MC}}\ \mathrm{T} \sum_i \frac{n(E_{\mathrm{rec}},\cos\theta_i)}{N(E_{\mathrm{MC}},\cos\theta_i)}\ \cos\theta_i\ \Delta\cos\theta_i;$$

Time Dependent MC Simulation

Shower Simulation

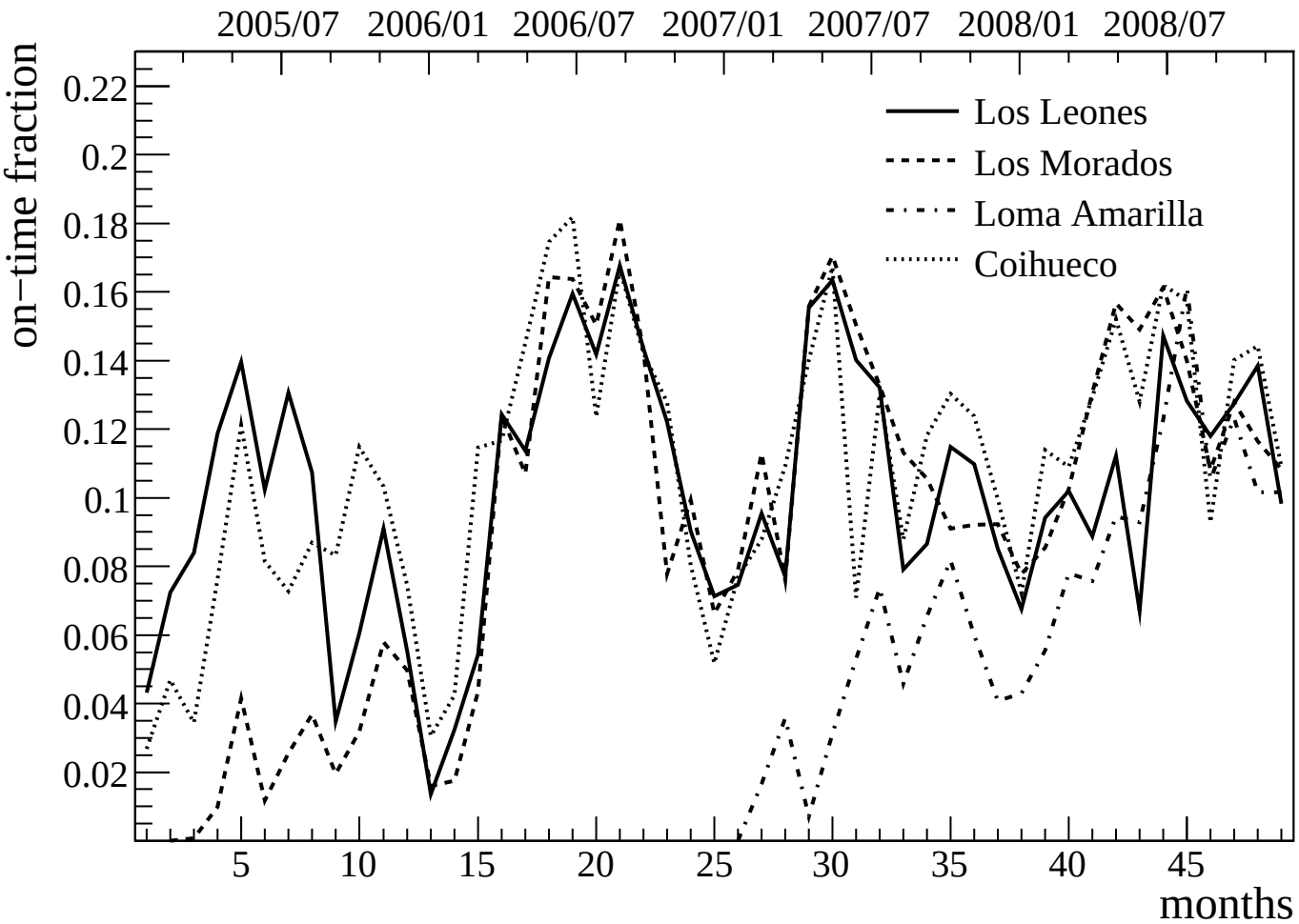
- CONEX shower profiles
- Full Simulation of the FD
- Parameterization of the time of the SD station

Simulation steps

- Choose a random time in the sidereal time
- Retrieve the on-time fraction
- Retrieve the characteristics of the detector (both FD and SD)
- Shower simulation(CONEX + atmosphere + detector)
- Reconstruction and selection

Cross-check performed using full CORSIKA+Geant4 simulations

On-time Calculation (2005 – 2008)



The uncertainty on the knowledge of the on-time is 4%

Selection Criteria

Profile Selections

- χ^2/Ndof of the profile <2.5
- $X_{\max}$ in the field of view
- Cherenkov light $<50\%$
- energy resolution $<20\%$
- hole in profile $< 20\%$

Atmospheric Selections

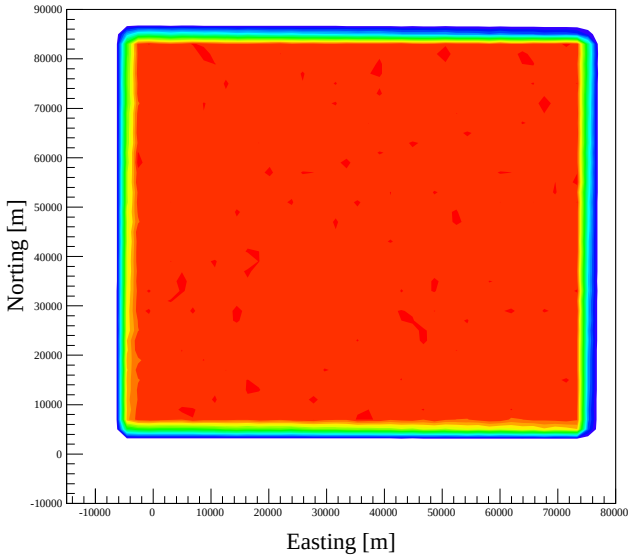
- lidar data available
- aerosol content measured
- cloud coverage $<25\%$

Fiducial Selections

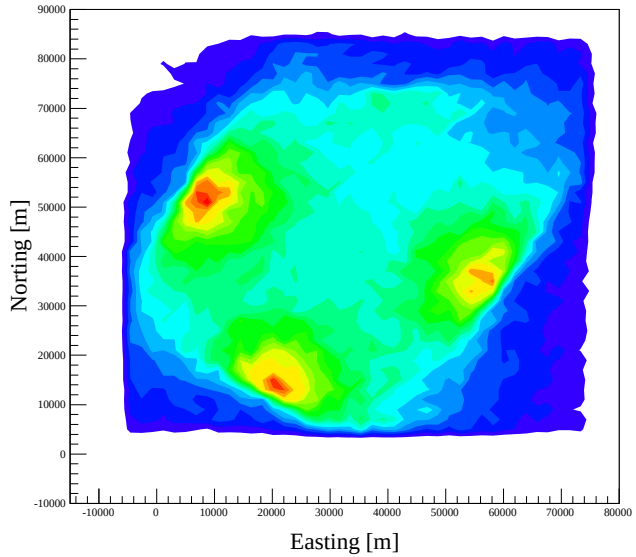
- energy of the shower $> 10^{18}$ eV
- zenith angle of the shower $< 60^{\circ}$
- station for the hybrid reconstruction within 1500 m from shower axis.
- fiducial cuts to remove dependences from primary composition and systematic energy shifts

Time Dependent MC Simulation

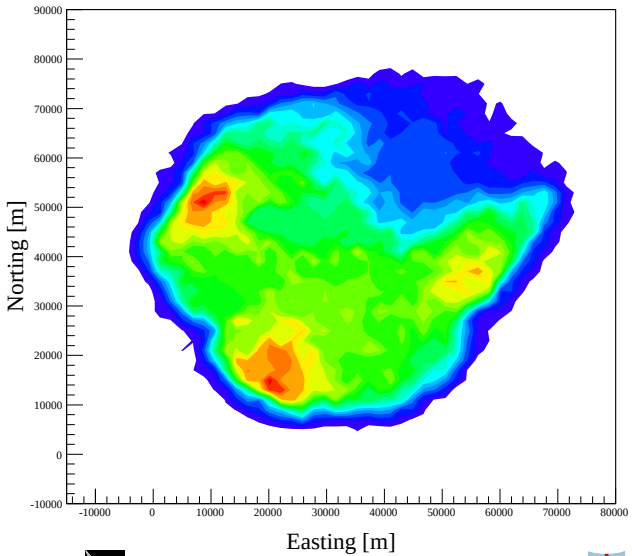
All Simulated



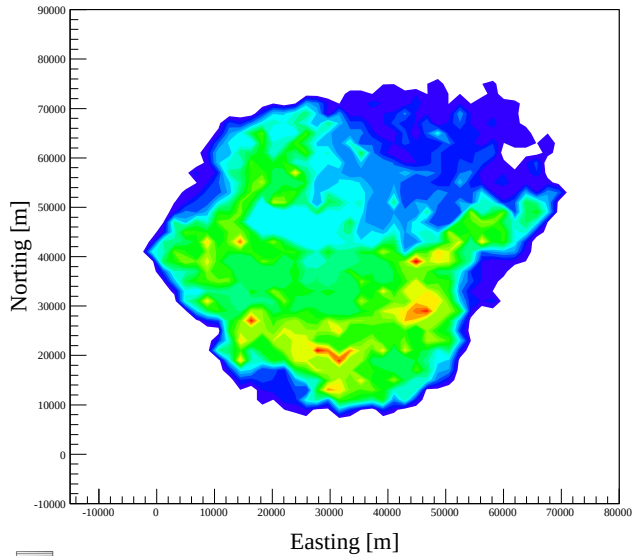
FD Trigger level



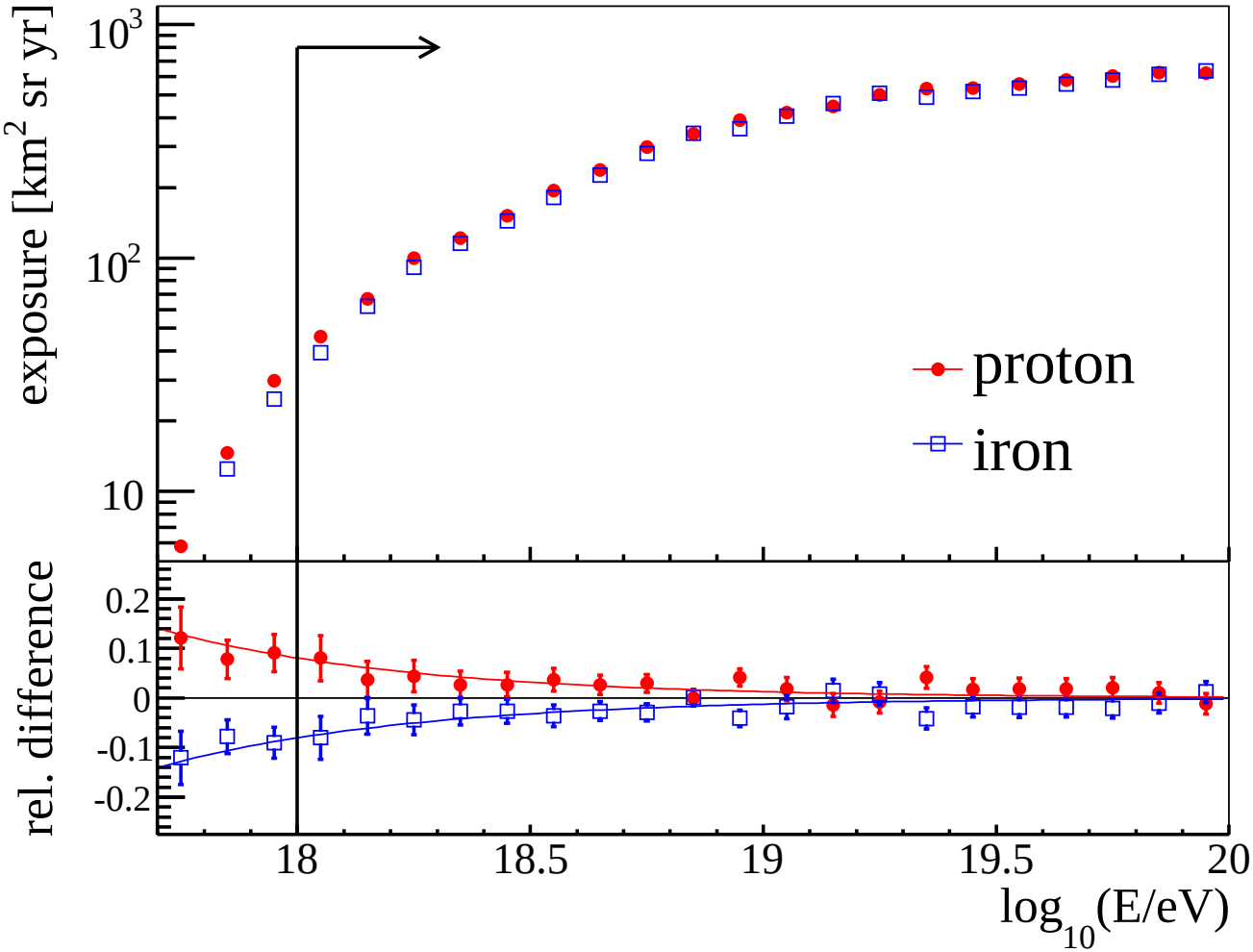
Hybrid Trigger level



Selection level



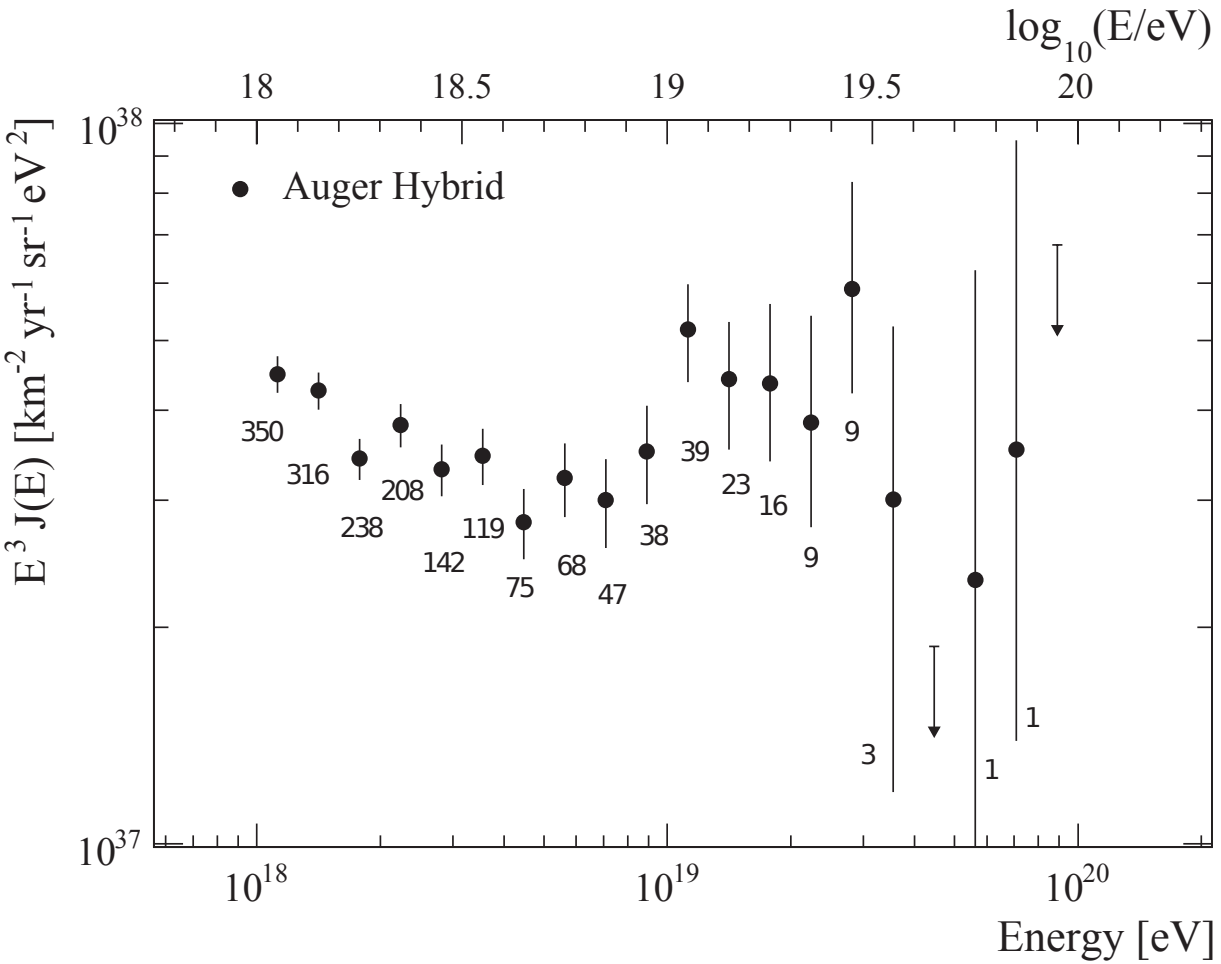
Hybrid Exposure - Nov 2005 / Jun 2008



Systematic uncertainty: ∼10% (∼6%)

- on-time ∼ 4%
- composition ∼ 8% (∼1%) at 10^{18} ($> 10^{19}$) eV
- hadronic interaction model ∼ 2%
- MC input spectra ∼ 2%

Hybrid Spectrum - Nov 2005 / Jun 2008



$$J(E) = \frac{\Delta N_{\rm sel}(E)}{\Delta E} \frac{1}{\mathcal{E}(E)}$$

About 1700 events

ANKLE FIT: broken power law

$$J(E) \propto \begin{cases} E^{-\gamma_1} & 10^{18}\ \text{eV} < E < E_{\rm ankle} \\ E^{-\gamma_2} & E_{\rm ankle} < E < 10^{19.5}\ \text{eV} \end{cases}$$

$$E_{\rm ankle} = 10^{18.65 \pm 0.09}\ \text{eV}$$
$$\gamma_1 = 3.28 \pm 0.07$$
$$\gamma_2 = 2.65 \pm 0.14$$
$$\chi^2/N_{\rm dof} = 10.2/11$$

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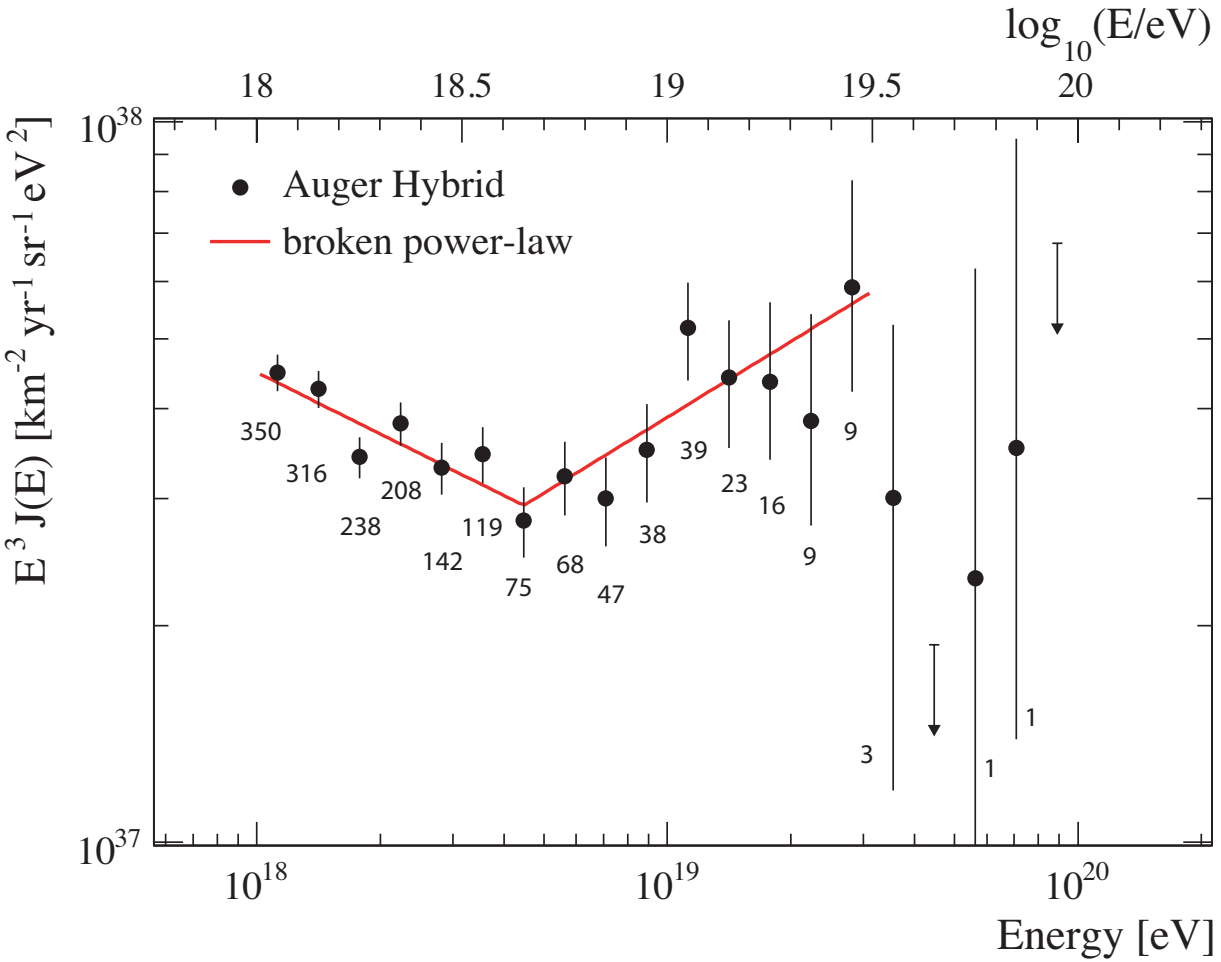

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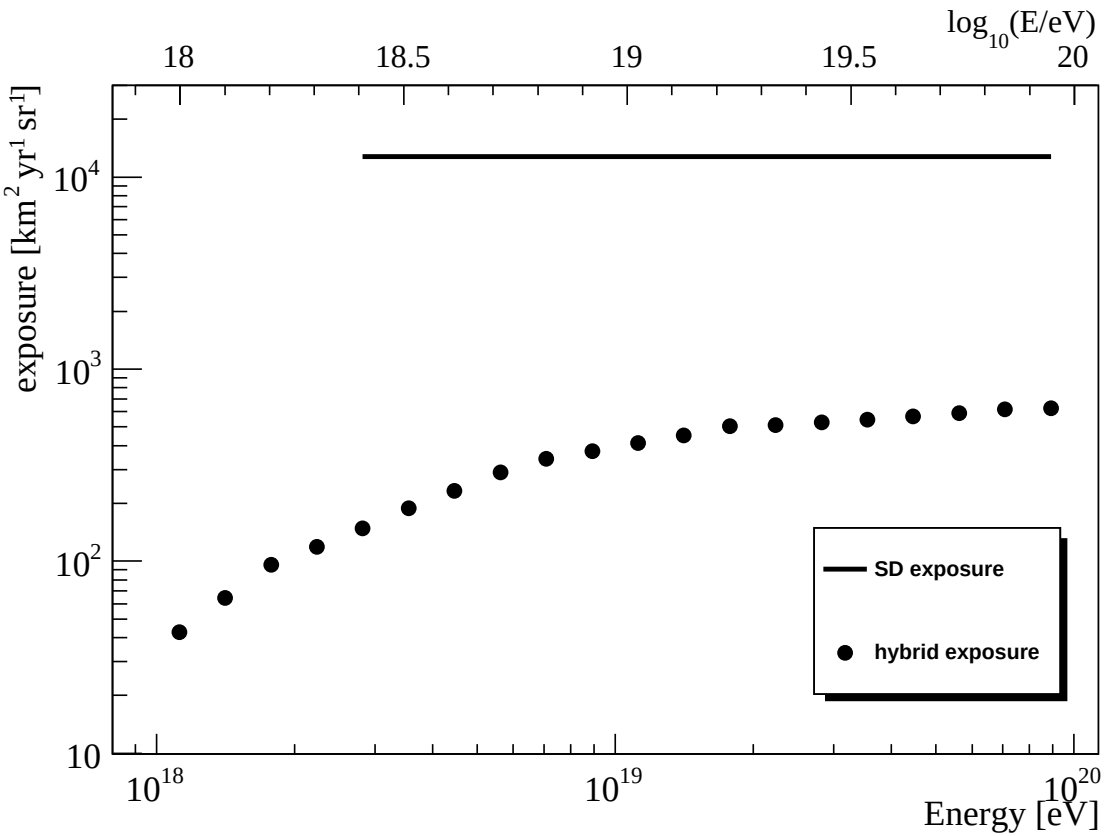
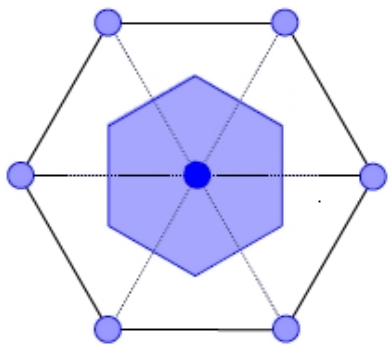
SD Spectrum - Jan 2004 / Dec 2008



- exposure: integrate the number of active elementary cells over the time
- total exposure: 12790 km^2 sr yr

Selection criteria

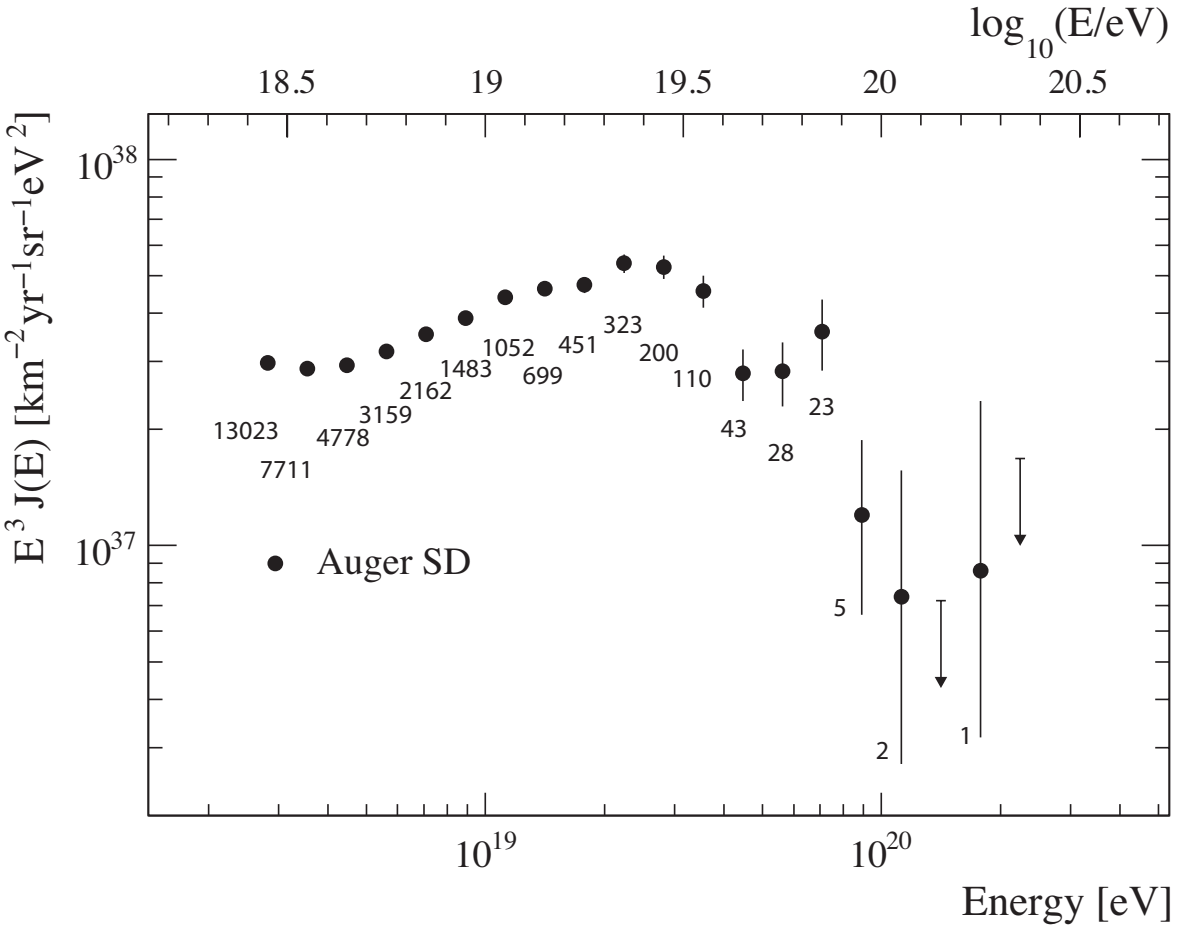
- $\theta < 60°$
- station with largest signal surrounded by 6 neighbors



Full trigger efficiency at $\sim$ 3 EeV

More than 3.5×10^4 events.

SD Spectrum - Jan 2004 / Dec 2008



$$J(E) = \frac{\Delta N_{\rm sel}(E)}{\Delta E} \frac{1}{\mathcal{E}(E)}$$

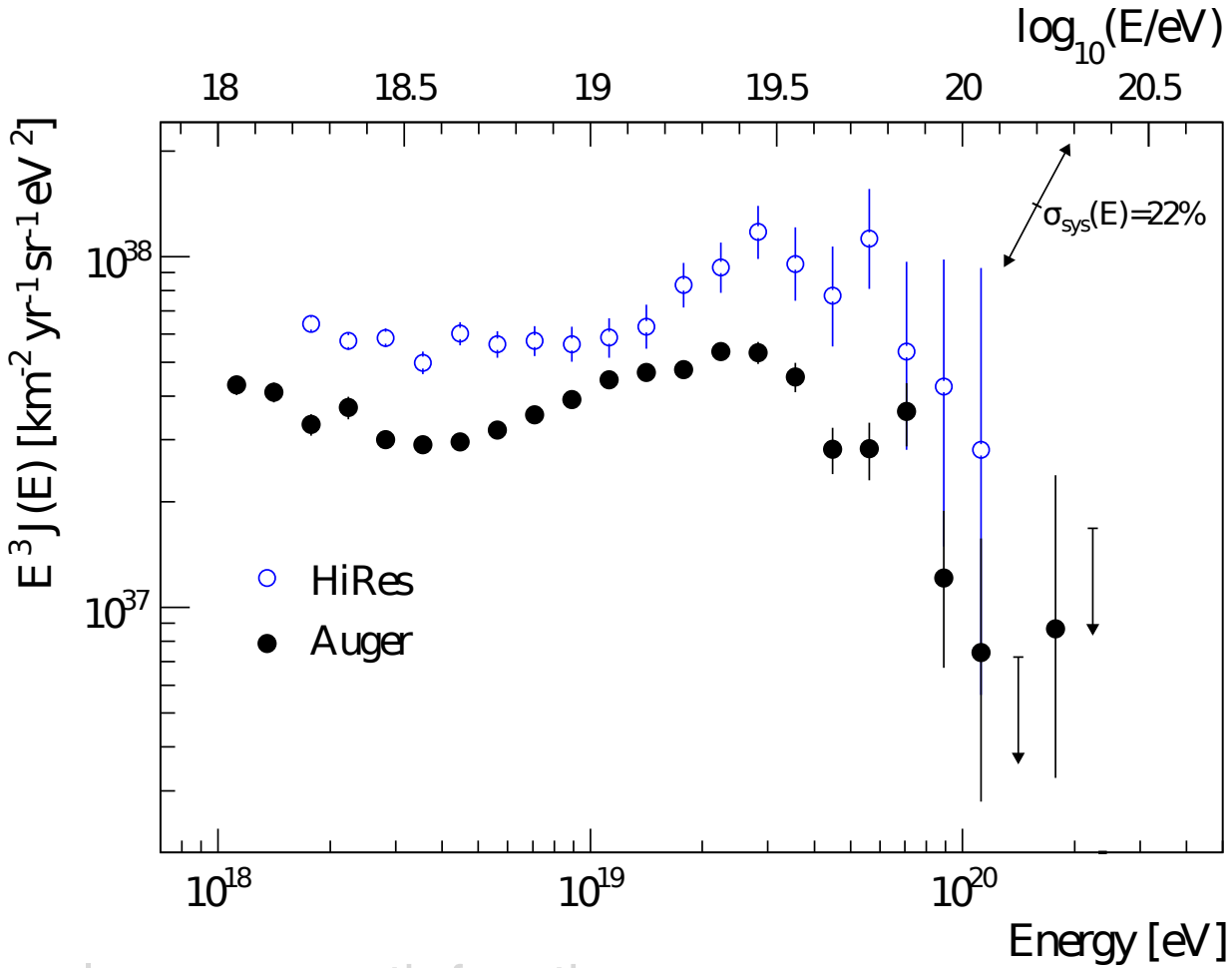
SD energy estimator calibrated with golden hybrid events

Systematic uncertainty in energy scale $\sim$ 22%

Systematic uncertainty: $\sim$6%

- exposure systematics $\sim$ 3%
- forward-folding analysis systematics $\sim$ 5%

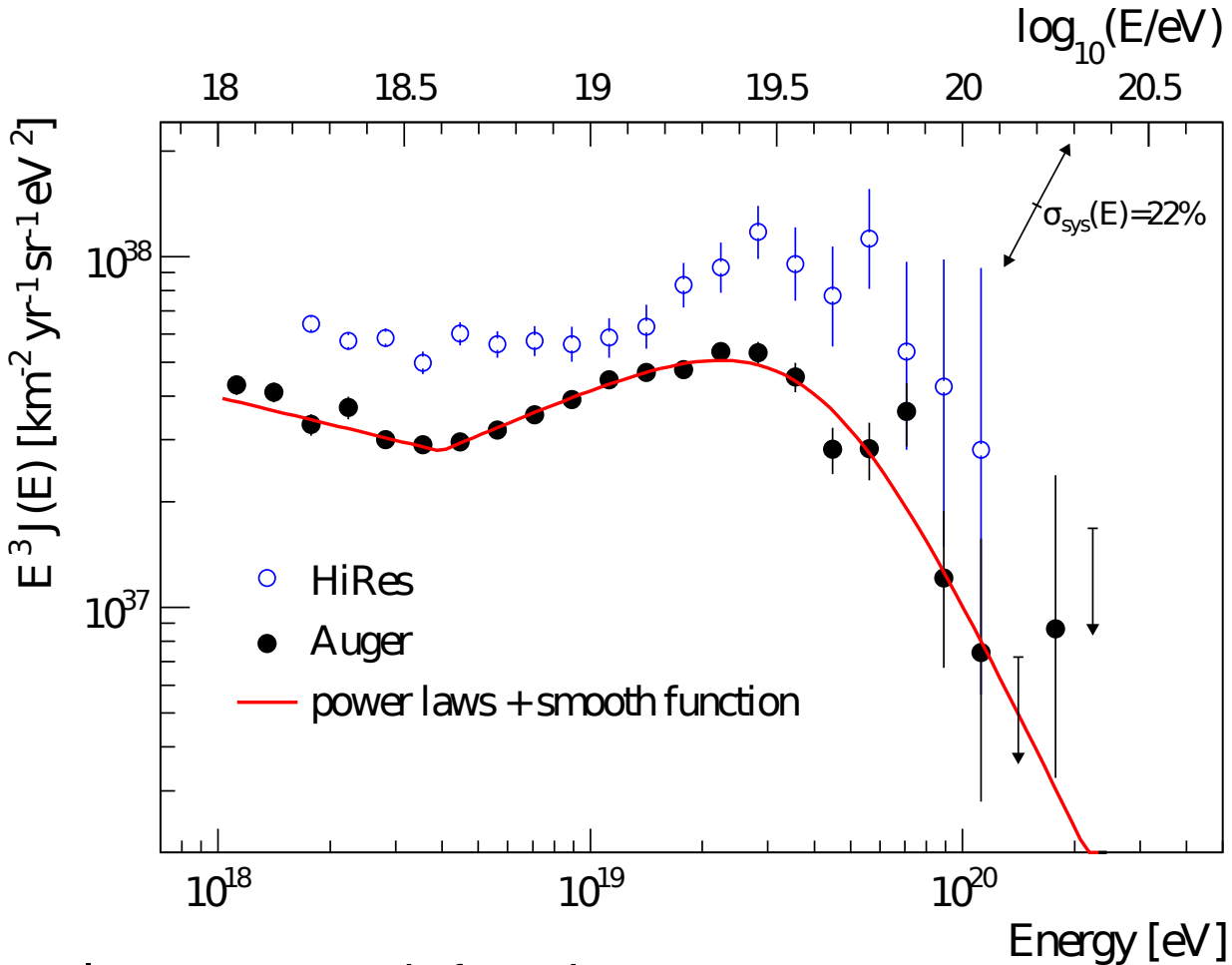
Combined spectrum - Jan 2004 / Dec 2008



FIT: power laws + smooth functions

- spectral indexes: 3.26 ± 0.04 and 2.55 ± 0.04
- ankle at $10^{18.60 \pm 0.01}$ eV
- flux reduced to one half w.r.t. power law at $10^{19.61 \pm 0.03}$ eV

Combined spectrum - Jan 2004 / Dec 2008



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Conclusions

- Data between 2004 and 2008 analysed
- Two independent spectra: SD and hybrid
- Hybrid exposure calculated using time dependent MC simulations
- Combination of the two spectra
- Ankle at $10^{18.60 \pm 0.01}$ eV
- Flux suppression by a factor 2 at $10^{19.61 \pm 0.03}$ eV
- Significance of the suppression larger than 20σ

THANK YOU !!!

References:
The Pierre Auger Collaboration, Phys. Lett. B 685 (2010) 239-246
The Pierre Auger Collaboration, Astrop. Phys. 34 (2011) 368-381
The Pierre Auger Collaboration, NIM A613 (2010) 29-39

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On-time Calculation

To follow the detector evolution, the on-time fraction has been calculated for each telescope as a function of time.

T_{width} = 10 min - compromise between statistics and accuracy

On-time fraction:

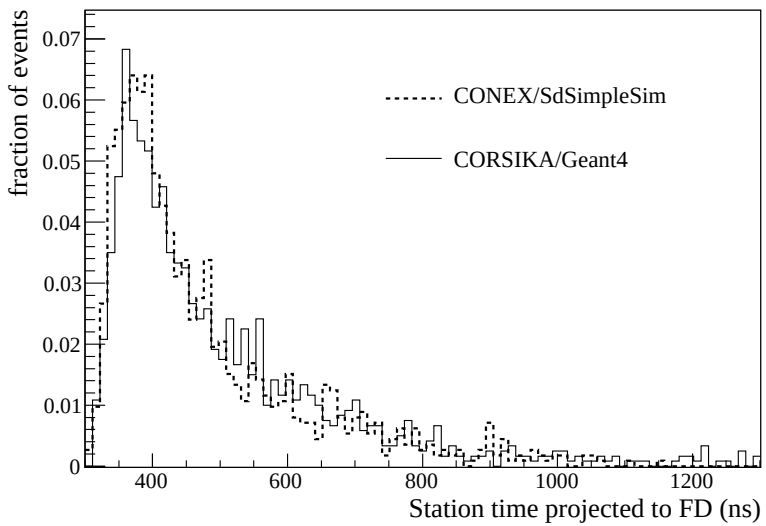
$$f(i,t) = \varepsilon_{\text{shutter}}(i,t)\cdot\varepsilon_{\text{DAQ}}(i,t)\cdot \cdot\varepsilon_{\text{Lidar}}(s,t)\cdot\delta_{\text{SD}}(s,t)$$

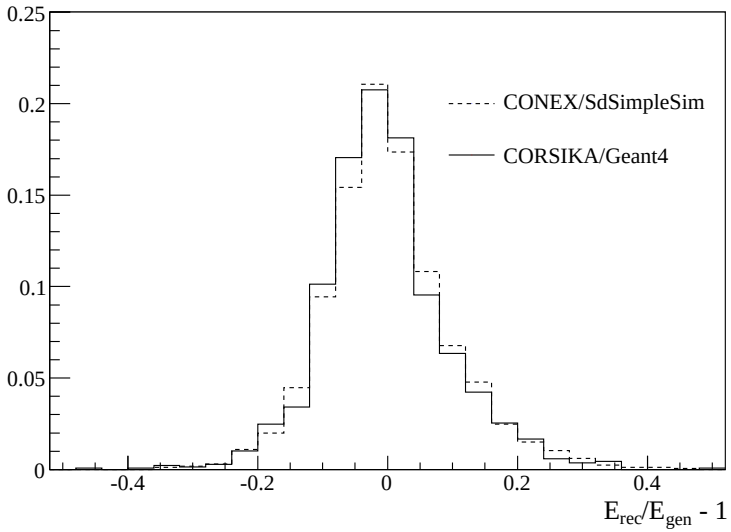
$i = tel$; $s = site$; $t = time$

Main contributions:

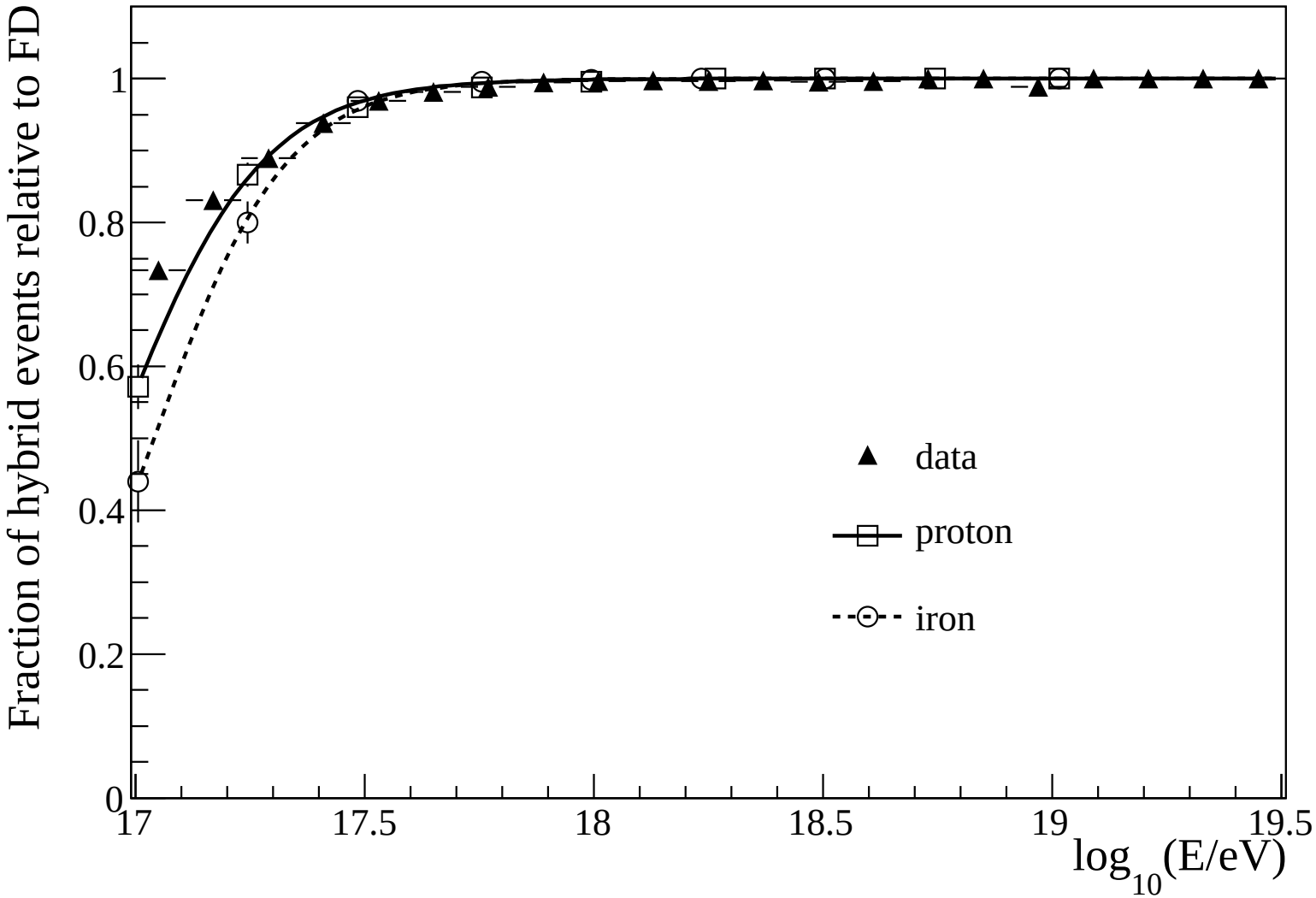
- $\varepsilon_{\text{shutter}}(i,t)$ Dead-time due to the closed shutters.
- $\varepsilon_{\text{DAQ}}(i,t)$ Dead-time due to the finite readout speed of the DAQ.
- $\varepsilon_{\text{Lidar}}(e,t)$ Veto from the activity of the atmospheric monitoring.
- $\delta_{\text{SD}}(e,t)$ Check of the status of the SD.

Time Dependent MC Simulation - Full MC comparison

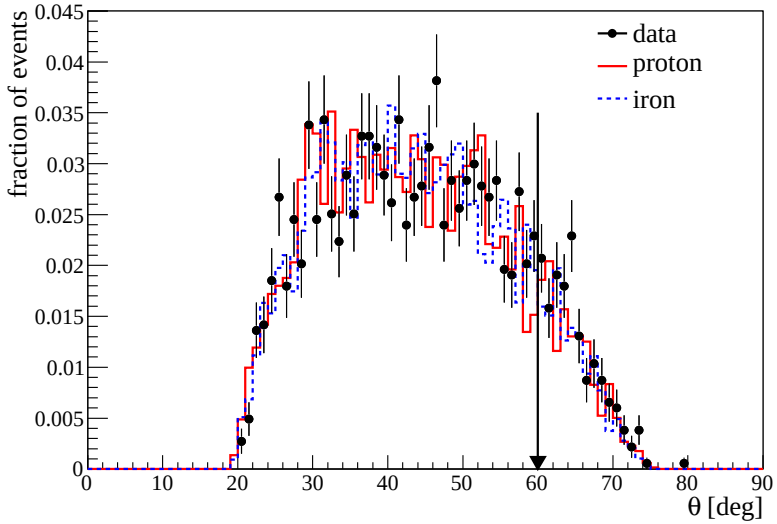




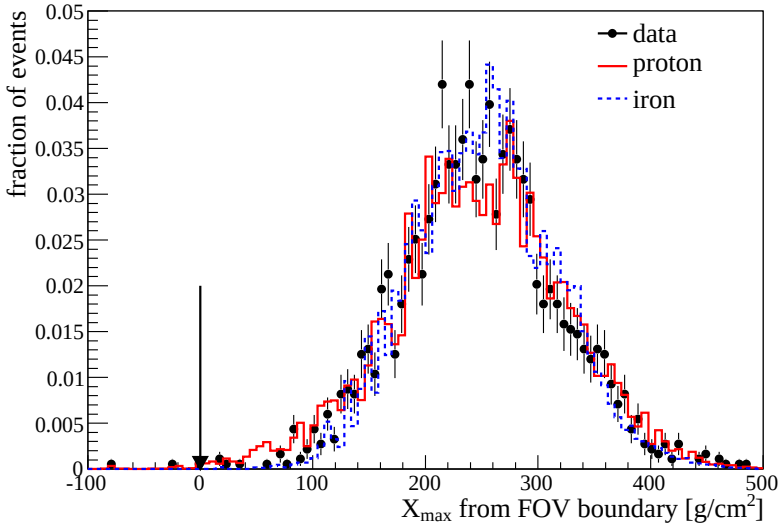
Hybrid Probability



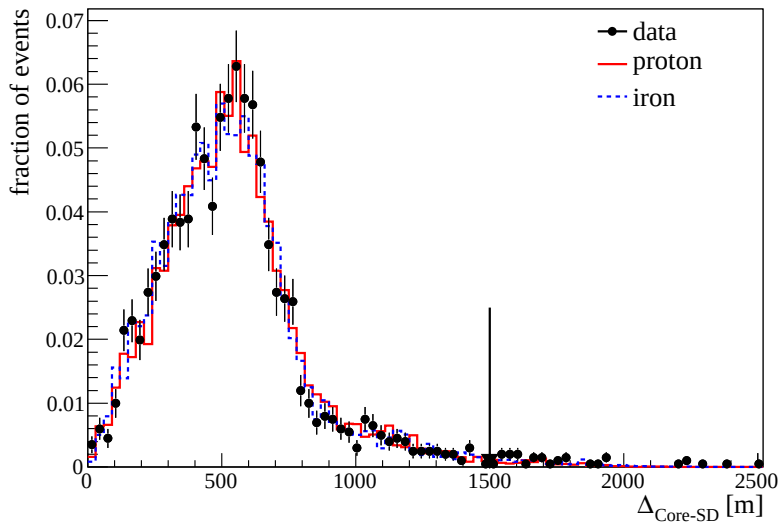
Cross Check - Data/MC Comparison



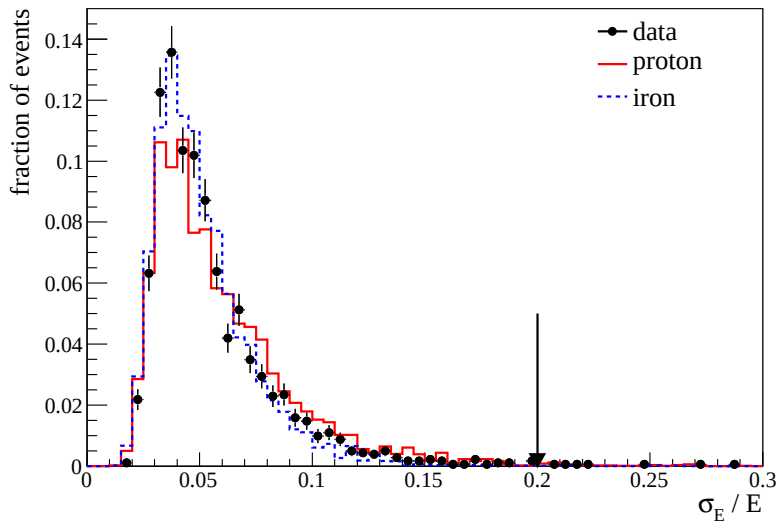
Zenith angle



Xmax in f.o.v

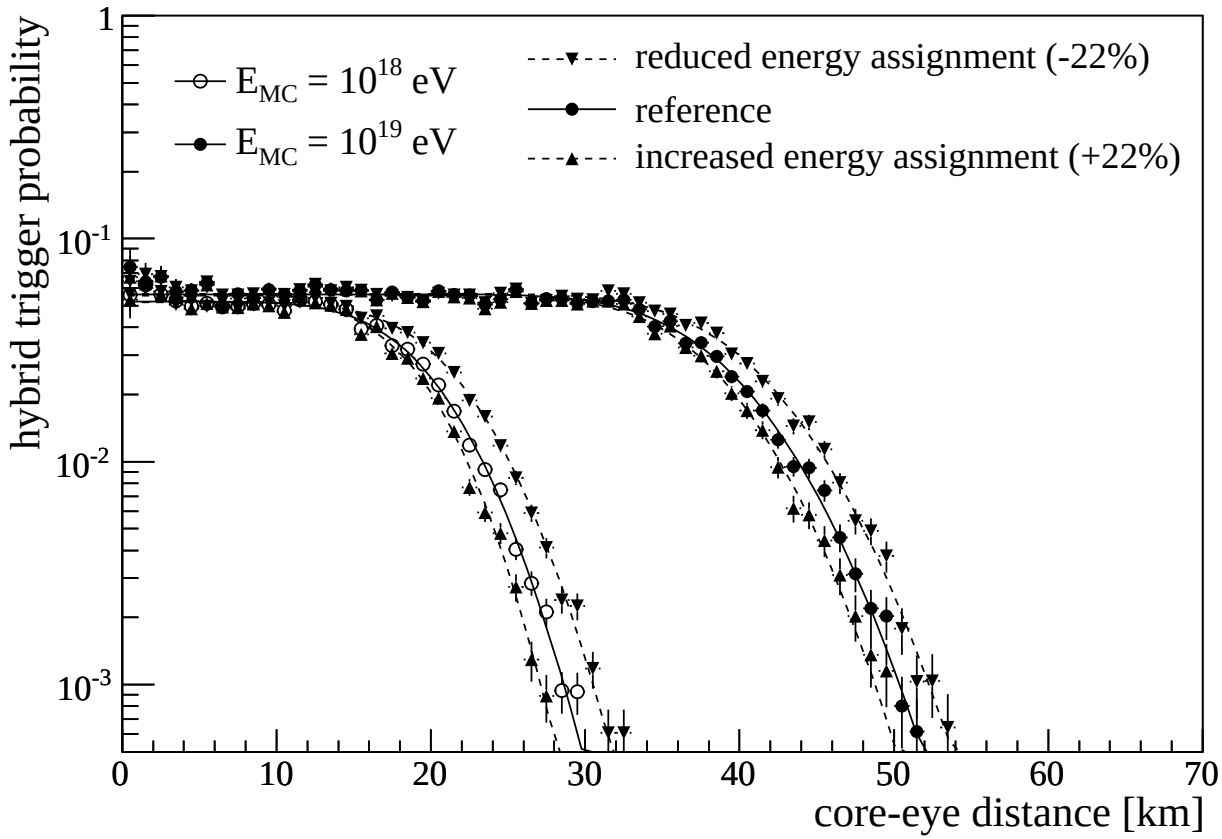


Core-station distance



Energy Reconstruction Error

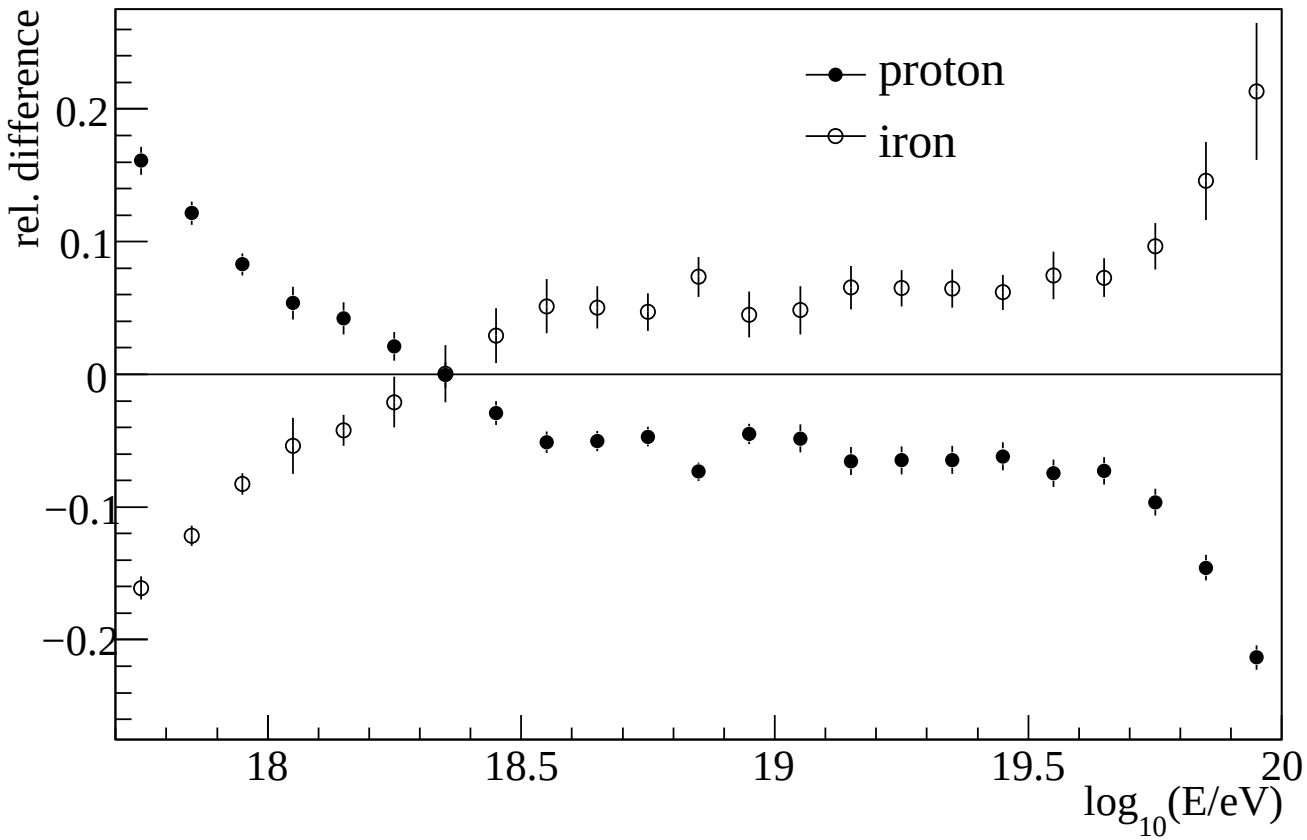
Fiducial Volume Cut - Energy scale



Trigger threshold dependence on a possible systematic energy shift removed by requiring the core to lie within a distance from the FD:

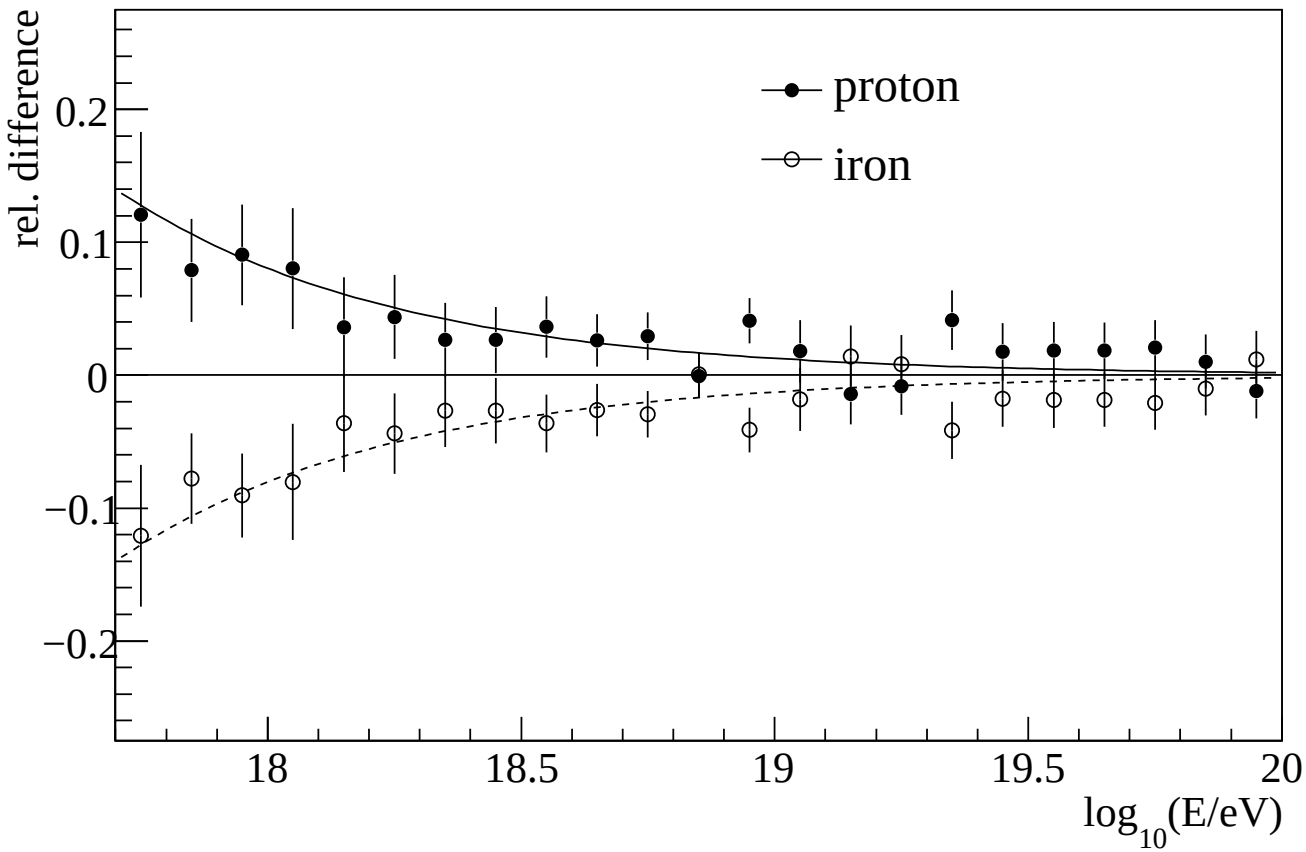
$$D_{\max}[\mathrm{km}] \leq \begin{cases} 24 + 12(\varepsilon - 19) & \text{for} \quad \varepsilon < 18.5 \\ 24 + 12(\varepsilon - 19) + 6(\varepsilon - 18.5) & \text{for} \quad \varepsilon \geq 18.5 \end{cases}$$

Field of View Cut - Mass Dependence



The limited field of view of the fluorescence detector and the requirements of observing the shower maximum introduce a different selection efficiency for different primary masses.

Field of View Cut - Mass Dependence



The systematic uncertainty on the mass composition is reduced to ∼8% (∼1%) at 10^{18} eV (above 10^{19} eV)

$$X_{\mathrm{up}}\ [g/cm^2] \geq 900 + 6 \cdot (\varepsilon - 18)$$

$$X_{\mathrm{low}}\ [g/cm^2] \leq \begin{cases} 550 - 61 \cdot (\varepsilon - 19.06)^2 & \text{for } \varepsilon < 19.06 \\ 550 & \text{for } \varepsilon \geq 19.06 \end{cases}$$