Università degli Studi di Torino
Scuola di Scienze della Natura
Dipartimento di Fisica

Tesi di Laurea Magistrale

Measurement of the energy spectrum of cosmic rays between 0.3 EeV and 30 EeV with data of the Infill array of the Pierre Auger Observatory

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Co-relatore: Dott.ssa Antonella Castellina

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Outline

- Introduction about **cosmic rays (CRs)** and the **energy spectrum**
- The **Pierre Auger Observatory** (PAO) detectors
- SD event: **energy reconstruction** steps using **Infill data of the PAO**
  - Estimation of the shower size
  - Correction for attenuation in atmosphere
  - Energy Calibration
- **Measurement of the energy spectrum**
  - Exposure computation
  - Unfolding procedure → **Unfolded spectrum**
- Evaluation of **systematic uncertainties**
- **Combination of vertical spectra** measured with the PAO

→ **spectrum in the energy region of transition** from galactic to extra-galactic CRs

(**~ 10^{17} eV - ~10^{19} eV**)

Cosmic rays

Cosmic rays are particles that reach the Earth's upper atmosphere from outside

Primary cosmic rays:

- p, e^-, H^+, He^{++} and heavier elements, γ, ν
- Accelerated at **astrophysical sources**
- **Energies** up to ~10^{20} eV
- Interaction with atmospheric nuclei and production of secondary cosmic rays

→ **Extensive Air Showers (EAS)**

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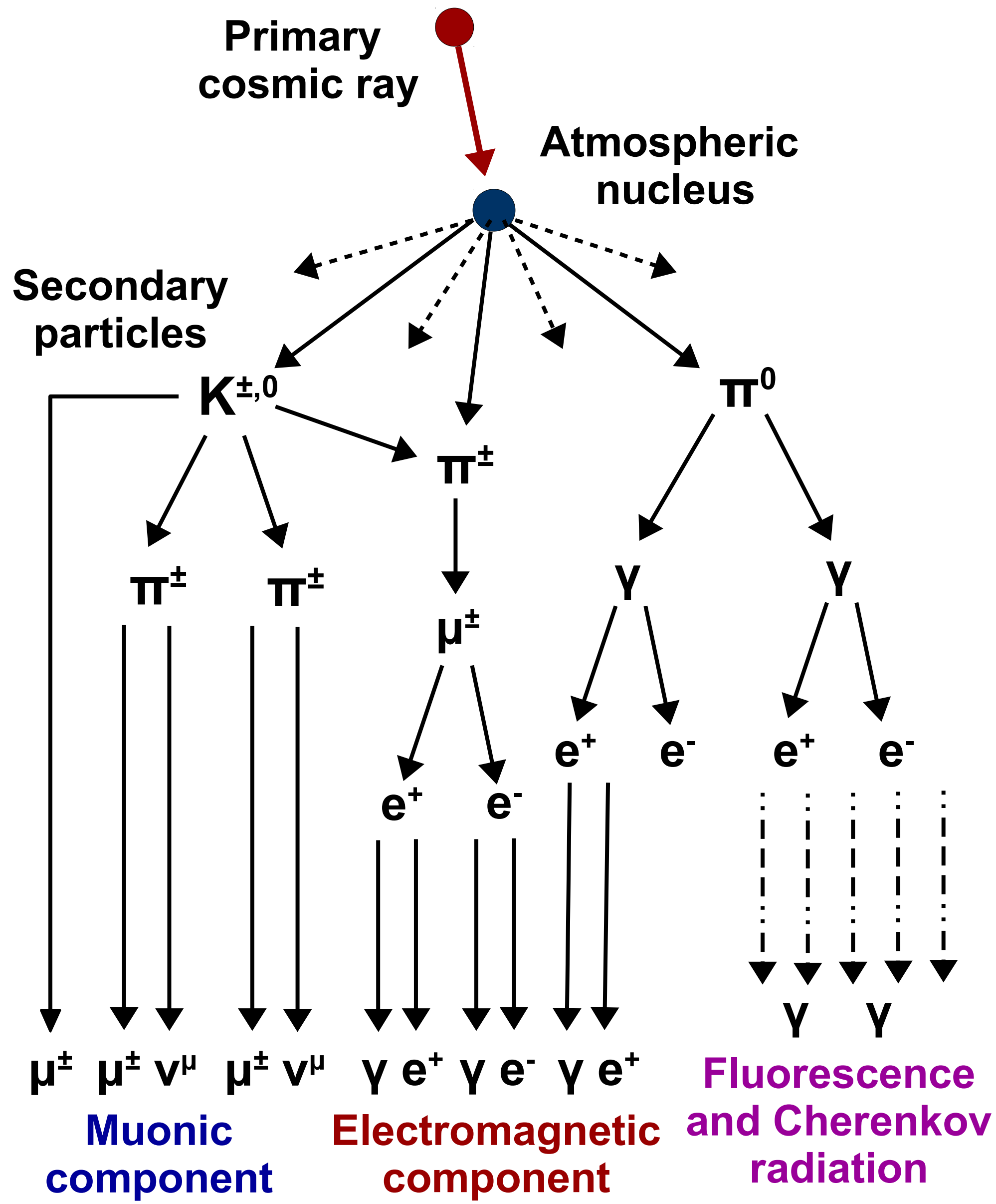
  ⟶ **Extensive Air Showers (EAS)**

Secondary cosmic rays:

- **Electromagnetic component**: **electrons, positrons and photons** from decays of charged and neutral mesons.
- **Muonic component**: **muons and muonic neutrinos** from decays of $K^{\pm}$ and $\pi^{\pm}$
- **Hadronic component** : **fragments** like p, n, π, K (remnants of the primary CR).



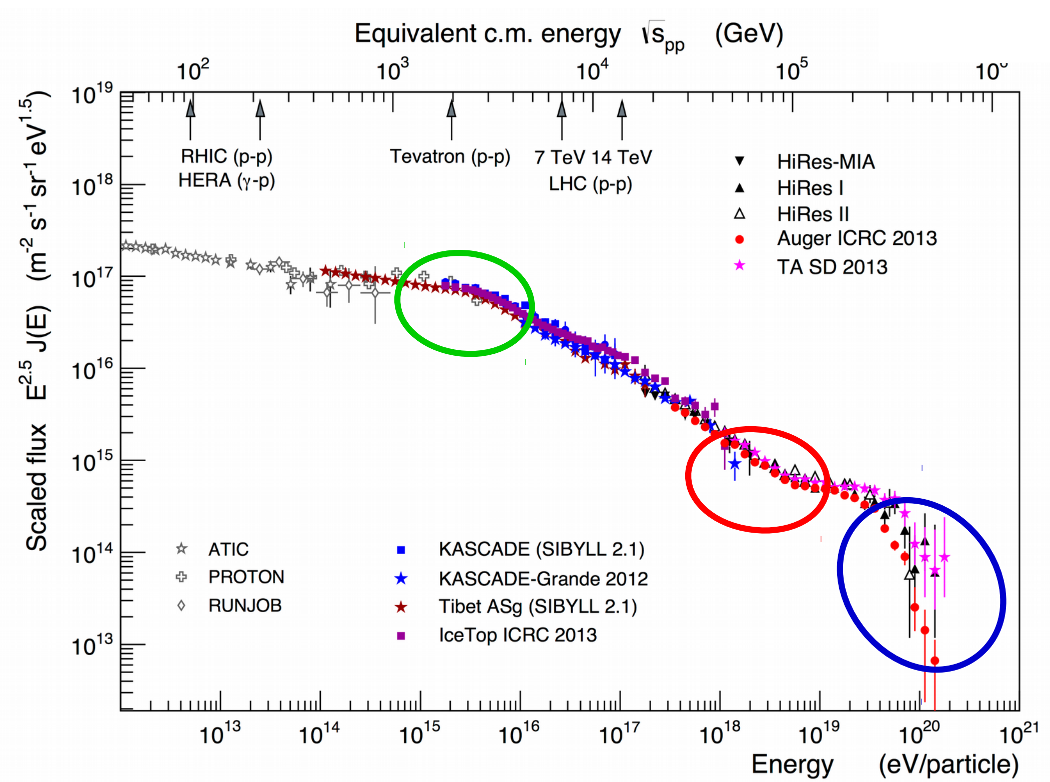
Physical quantities

Information about sources and propagation of CRs obtained from **3 physical quantities**

1) **Arrival direction** : The **flux** is **isotropic**: charged CRs ⟶ deflected by magnetic fields in the interstellar medium (expecially at low energies)

2) **Mass composition** : Different abundances of light and heavy components at different energies

3) **Energy** : Energy spectrum reconstruction



The flux vs energy follows a **steep power law** : $\sim E^{-\gamma}$ **($\gamma \sim 3$)**

↓

Decreasing with increasing energy

Some features in the spectrum:

- **Knee** → steepening
- **Ankle** → hardening
- **Suppression**

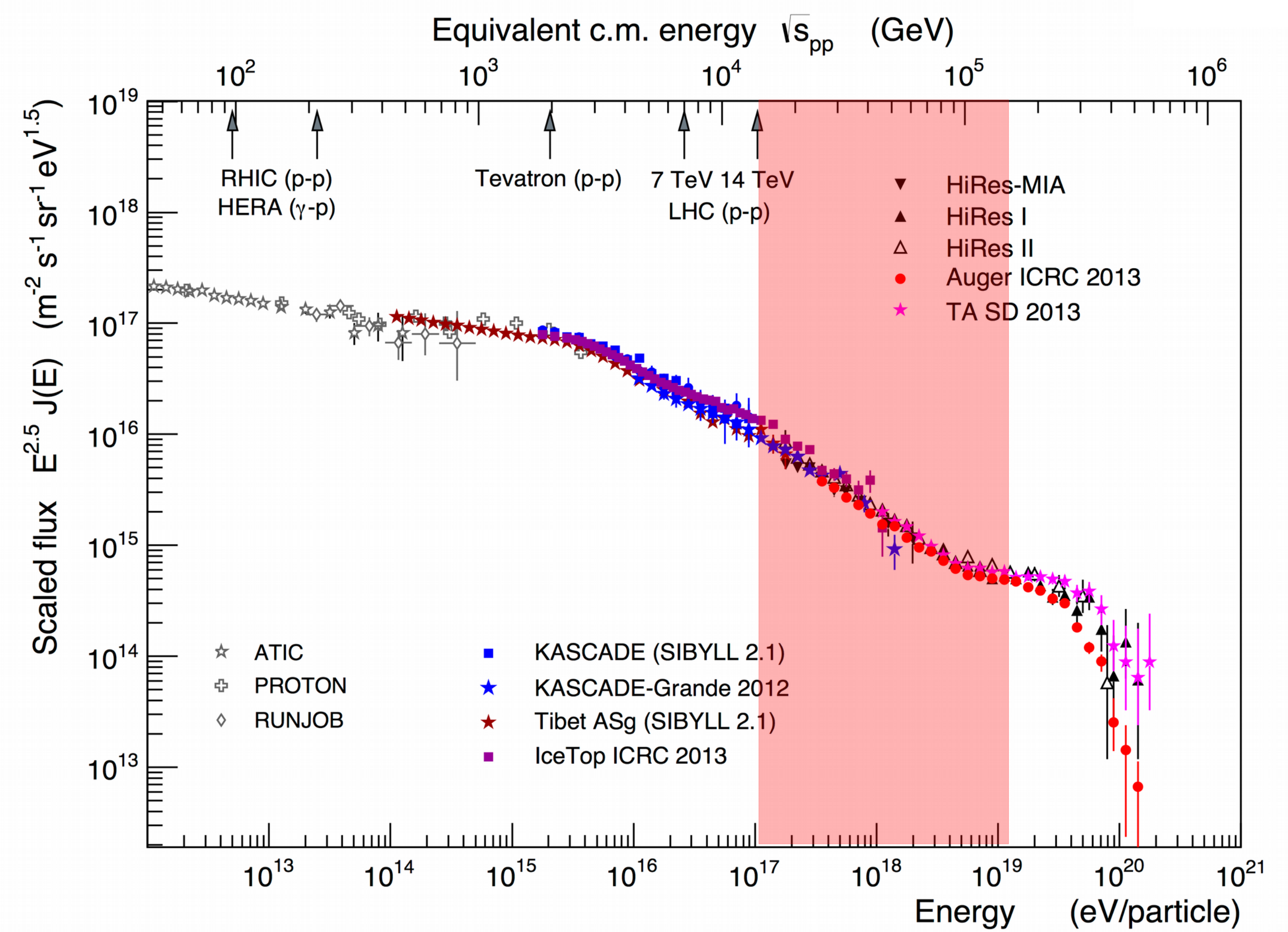
} **Slope changes**

⟶ **Hints about CRs origin**

The energy spectrum

- **Transition region** between galactic and extra-galactic origin

- **Onset of the extra-galactic (EG) component**
- Theoretical models: different predicted transition energies → open astrophysical problem



The energy spectrum

➢ <u>**Transition region**</u> between galactic and extra-galactic origin

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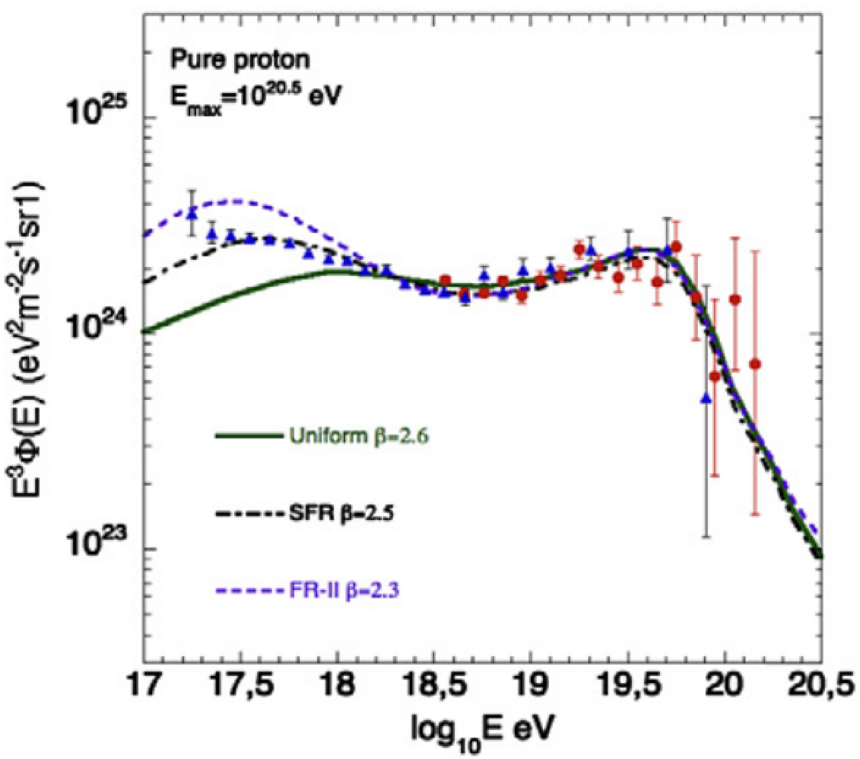
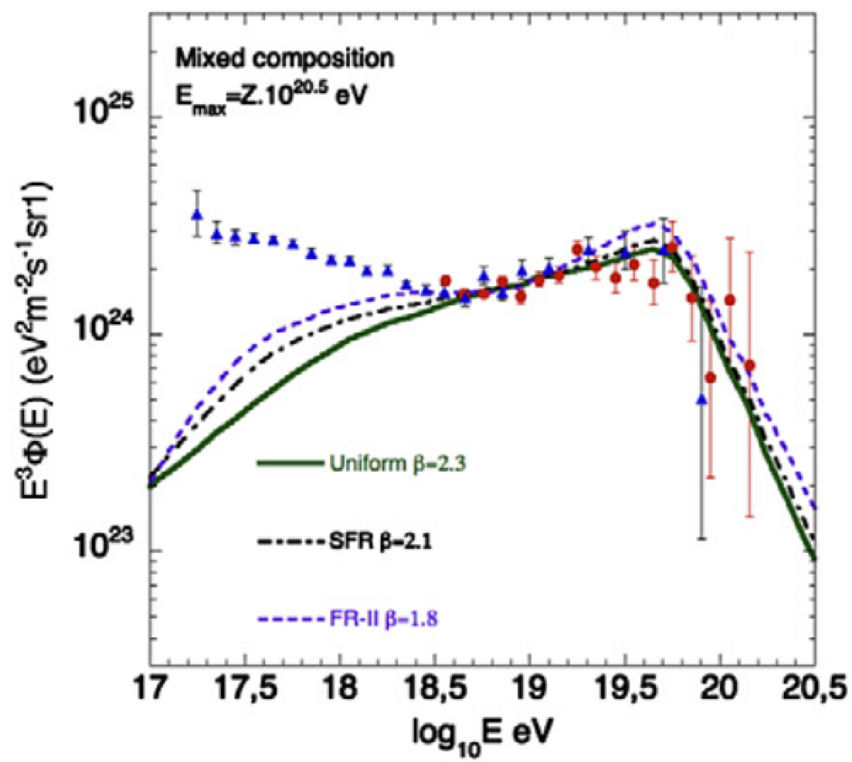
Dip model



Mixed composition model



- EG component : mainly protons (<10-15% of heavier nuclei allowed)
- Transition at ~ $7 \cdot 10^{17}$ eV

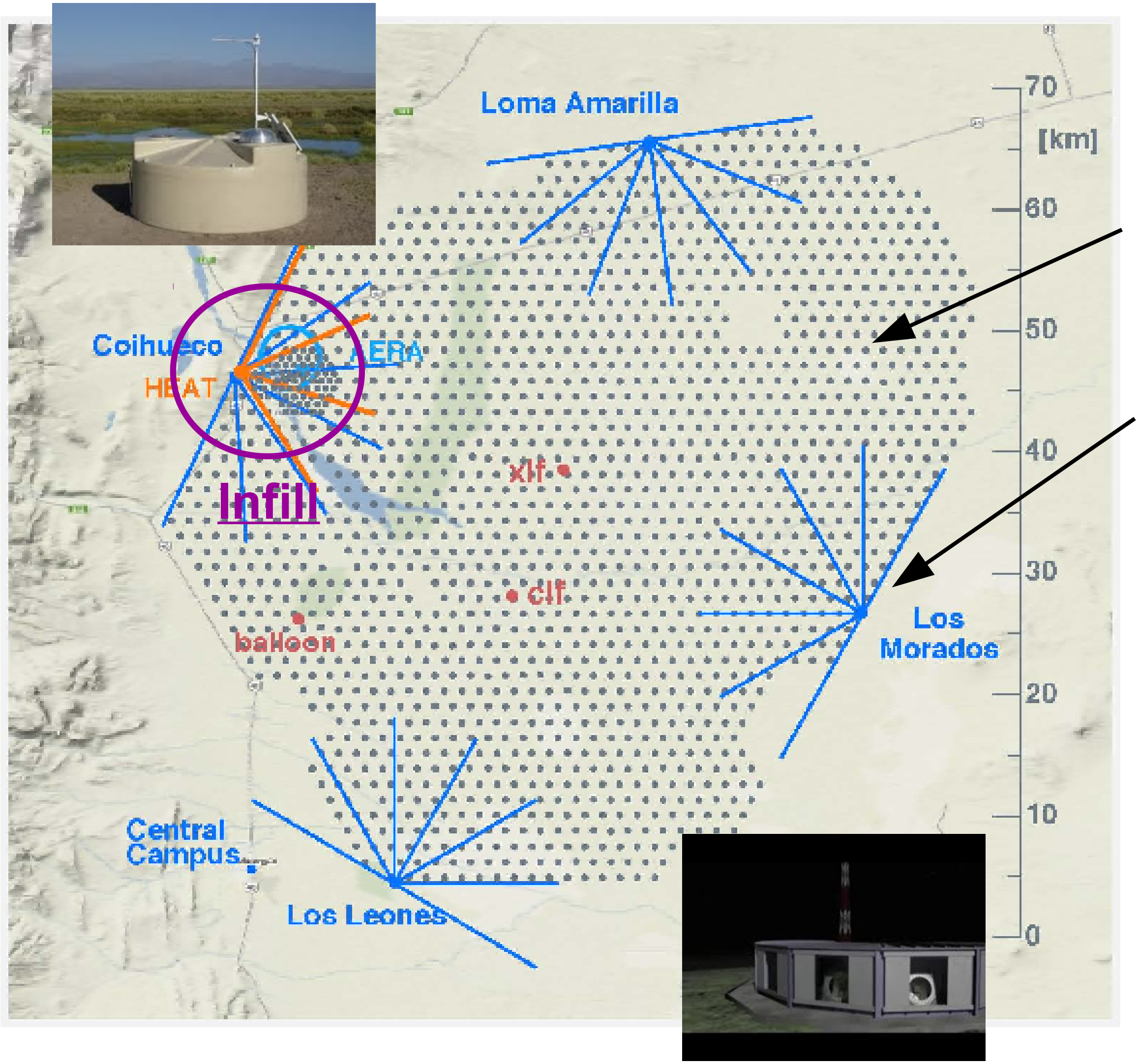
- EG component : mixed composition (similar to the galactic one)
- Transition at ~ $3 \cdot 10^{18}$ eV

The Pierre Auger Observatory

The Pierre Auger Observatory

Hybrid detector located in Argentina, near Malargue, studying ultra-high energy cosmic rays (**UHECR**)

Surface detector (**SD**) + Fluorescence detector (**FD**)



Energy range: ~10^{17} eV - ~10^{20} eV

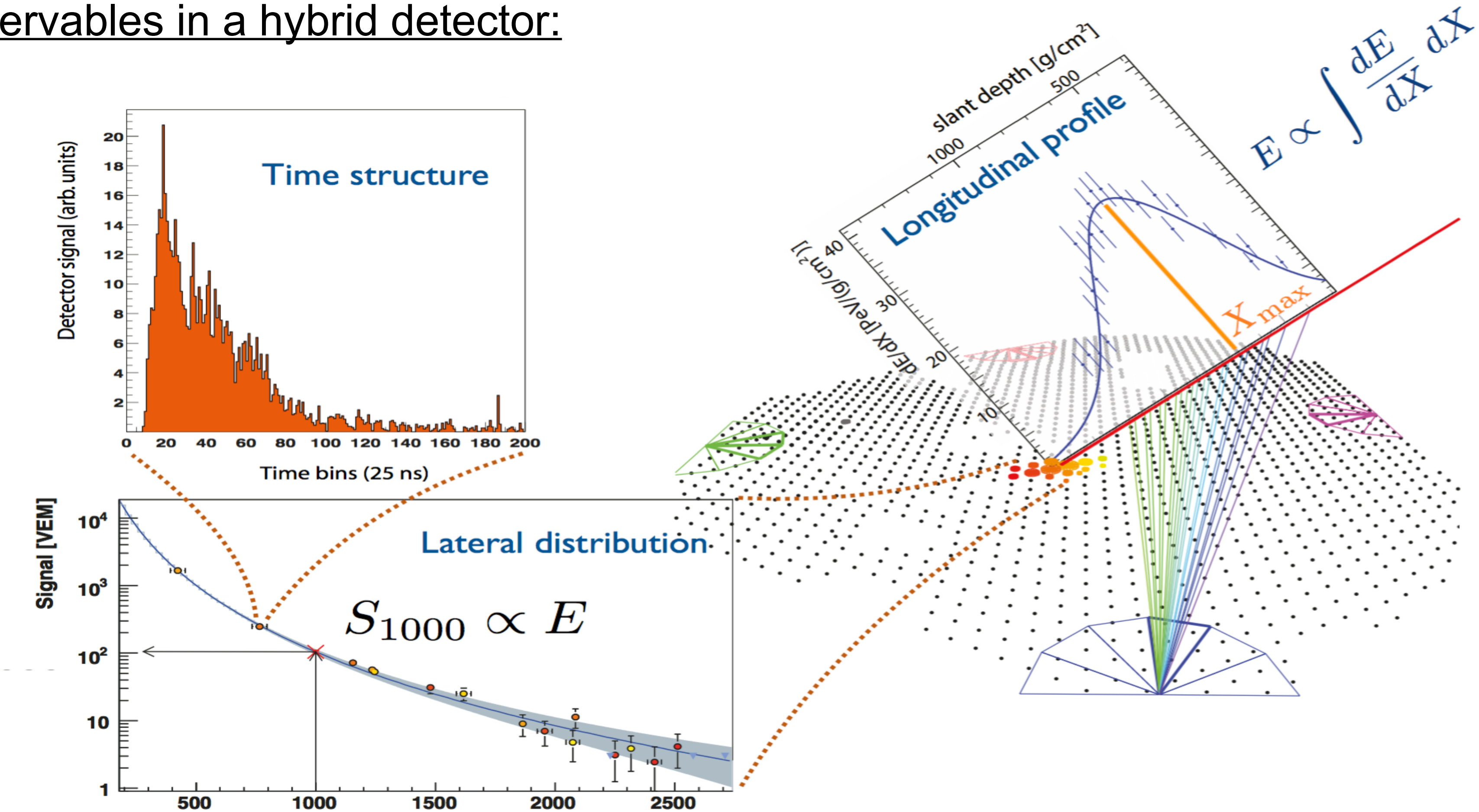
- **SD**: **Water-Cherenkov tanks**
  1600 in a 1.5 km grid (3000 km^2)
  61 in 0.75 km **infill** grid (~30 km^2)
- **FD**: **Fluorescence Telescopes**
  24 in 4 buildings overlooking SD
  3 in 1 building overlooking the **Infill**
- **Underground Muon detectors**
  engineering array phase
  in the Infill array
- **AERA radio antennas**
  153 in 17 km^2
- **Atmospheric monitoring stations**

The Pierre Auger Observatory

Surface detector (**SD**) + Fluorescence detector (**FD**)

duty cycle ~100% duty cycle ~15%

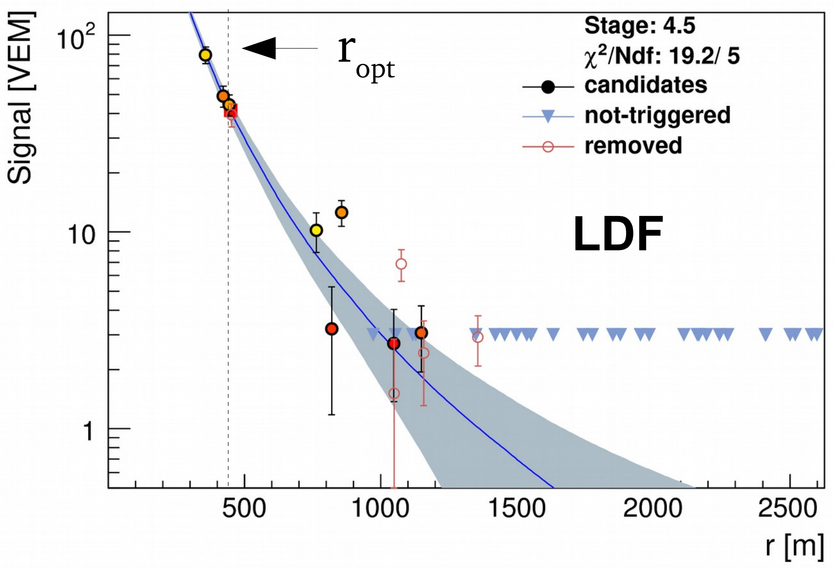
<u>Observables in a hybrid detector:</u>



Hybrid events : those observed by both detectors

SD event reconstruction

- EAS triggering the Infill array → stations register **sizes** (S [VEM]) **and times** of signals



- Reconstruction of the **Lateral Distribution Function** (S vs radial distance from the core)

$$S(r) = S_{450}\left(\frac{r}{450\,m}\right)^{\beta}\left(\frac{r+r_1}{450\,m+r_1}\right)^{\beta+\gamma}$$

signal at the optimal distance of $\mathbf{r_{opt}}$ **= 450 m**

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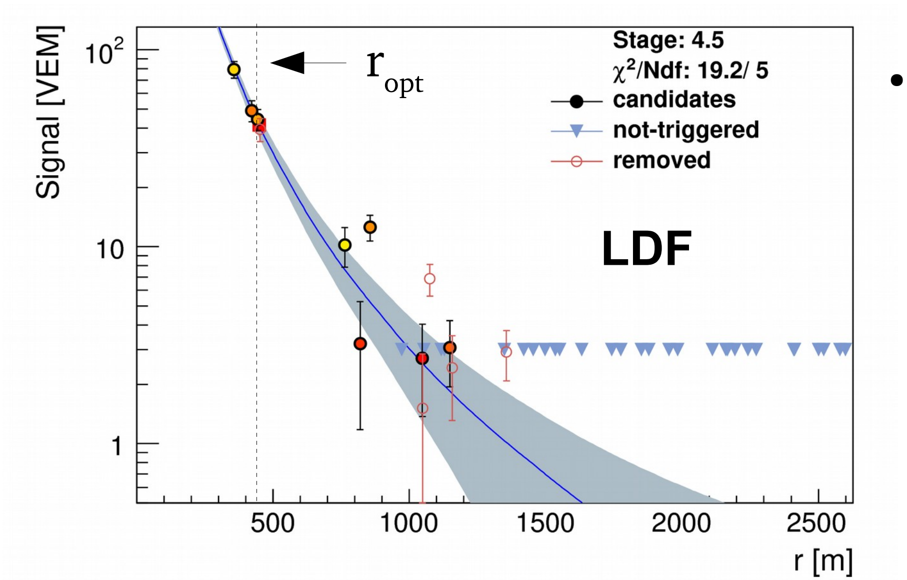

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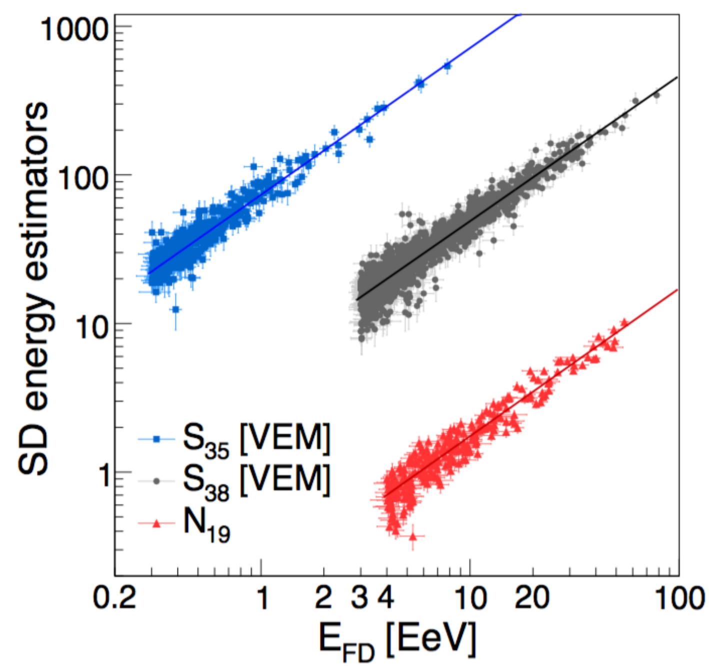
- Correction for **attenuation in atmosphere**:

$S_{450}(E,\theta)$ —**Costant Intensity Cut**→ **estimator $S_{35}(E)$**

- **Energy calibration**: S_{35} → **energy E**

$$E(S_{35}) = A\cdot\left(\frac{S_{35}}{VEM}\right)^{B}$$

A= 12.87 · 10^{15} eV
B= 1.0128



Event selection

Data used for this analysis:

Events collected **with SD-750 from 01/08/2008 to 29/02/2016**

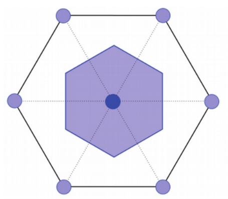
Criteria of data section:

- **Good reconstruction level**

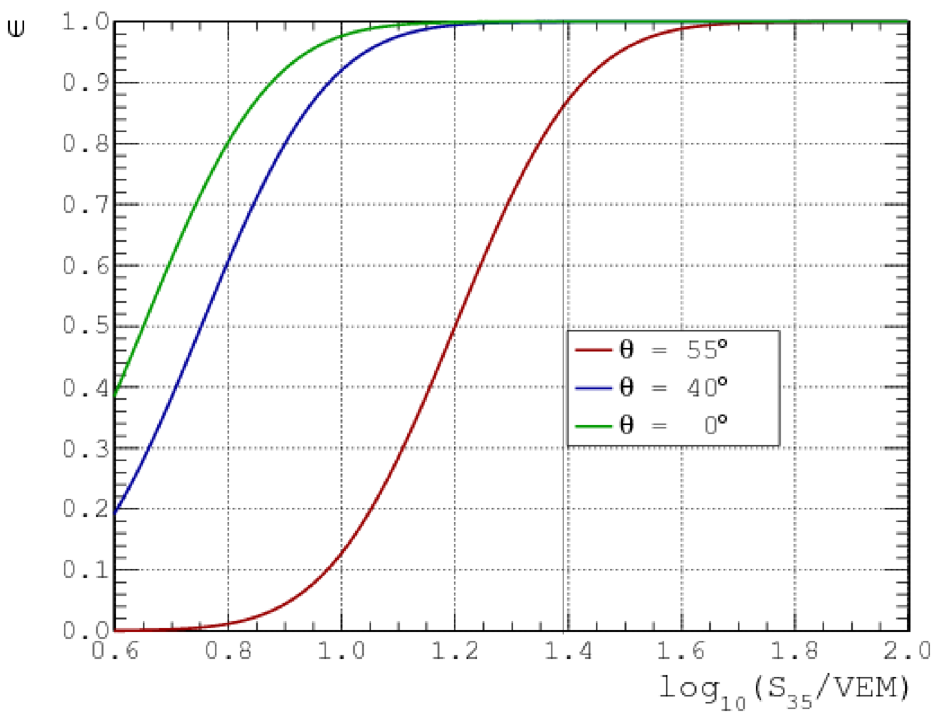
  → well reconstructed lateral distribution function

- **6T5 trigger**

  → detector with the highest signal sourrounded by a working hexagon.



Cuts	N. of events after cuts
-	2 983 081
RecLevel=3	2 976 894
T4	2 976 472
T5	1 814 083
$\theta < 55°$	1 771 158
Bad Periods	**1 695 363**



- **Zenith angle** θ lower than 55°

  → full efficiency above the $E_{thr} = 3 \cdot 10^{17}$ eV

- Rejection of events in bad periods

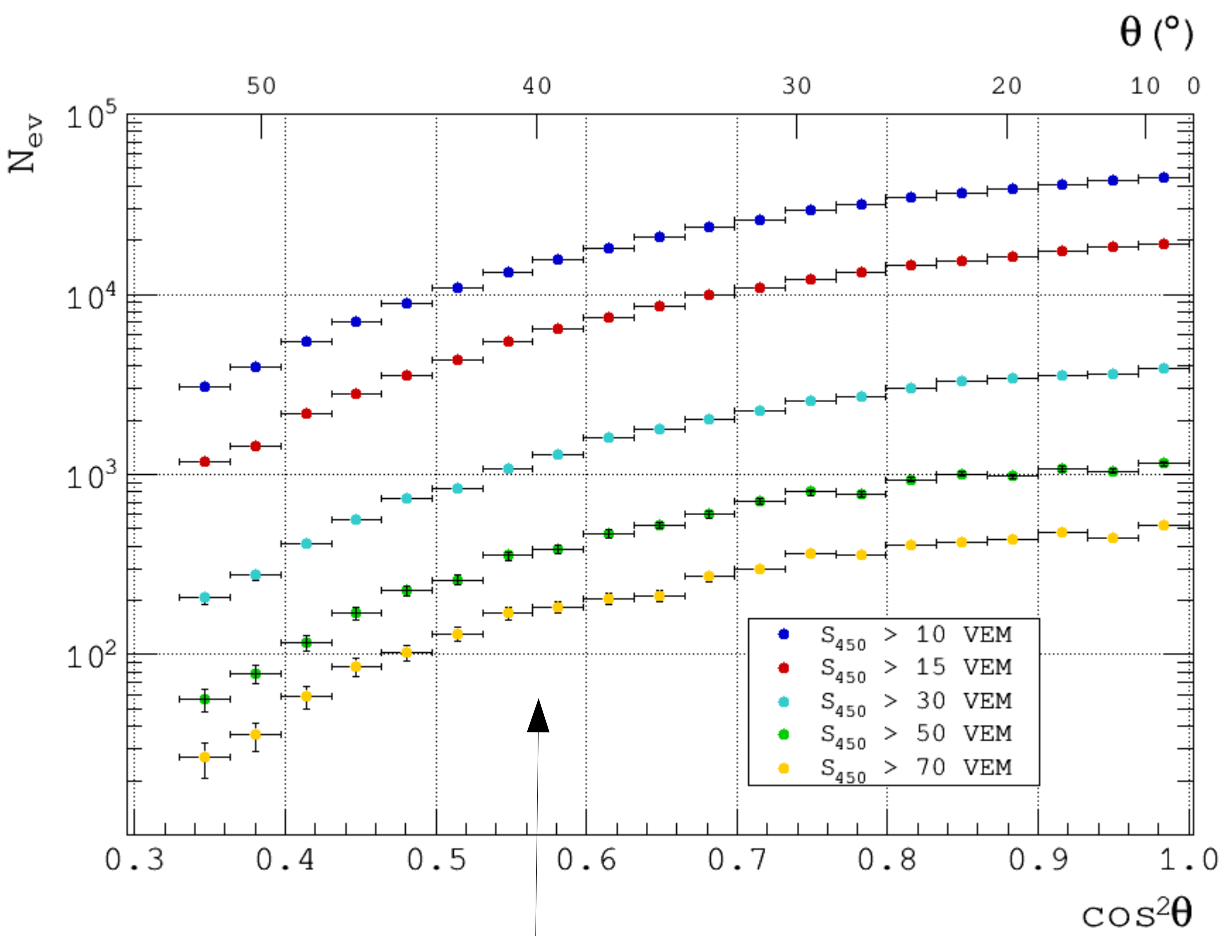
1 695 363 events for the updated Infill spectrum

Correction for attenuation in atmosphere

Attenuation of showers in atmosphere

Isotropy of cosmic ray flux ⟶ Above the full efficiency threshold E_{thr}: $\frac{dI}{d\cos^2\theta} = const$

S_{450} is the shower size estimator from the LDF fit



Non-uniform distribution
for any cut

Particles with larger θ interact more times in atmosphere

↓

Attenuated signals at ground

The shower size estimator S_{450} depends on both E and θ

The **Constant Intensity Cut Method** factorizes the zenith angle dependence through the attenuation function CIC(θ)

$$S_{450}(E,\theta) = S_{35}(E) \cdot CIC(\theta)$$

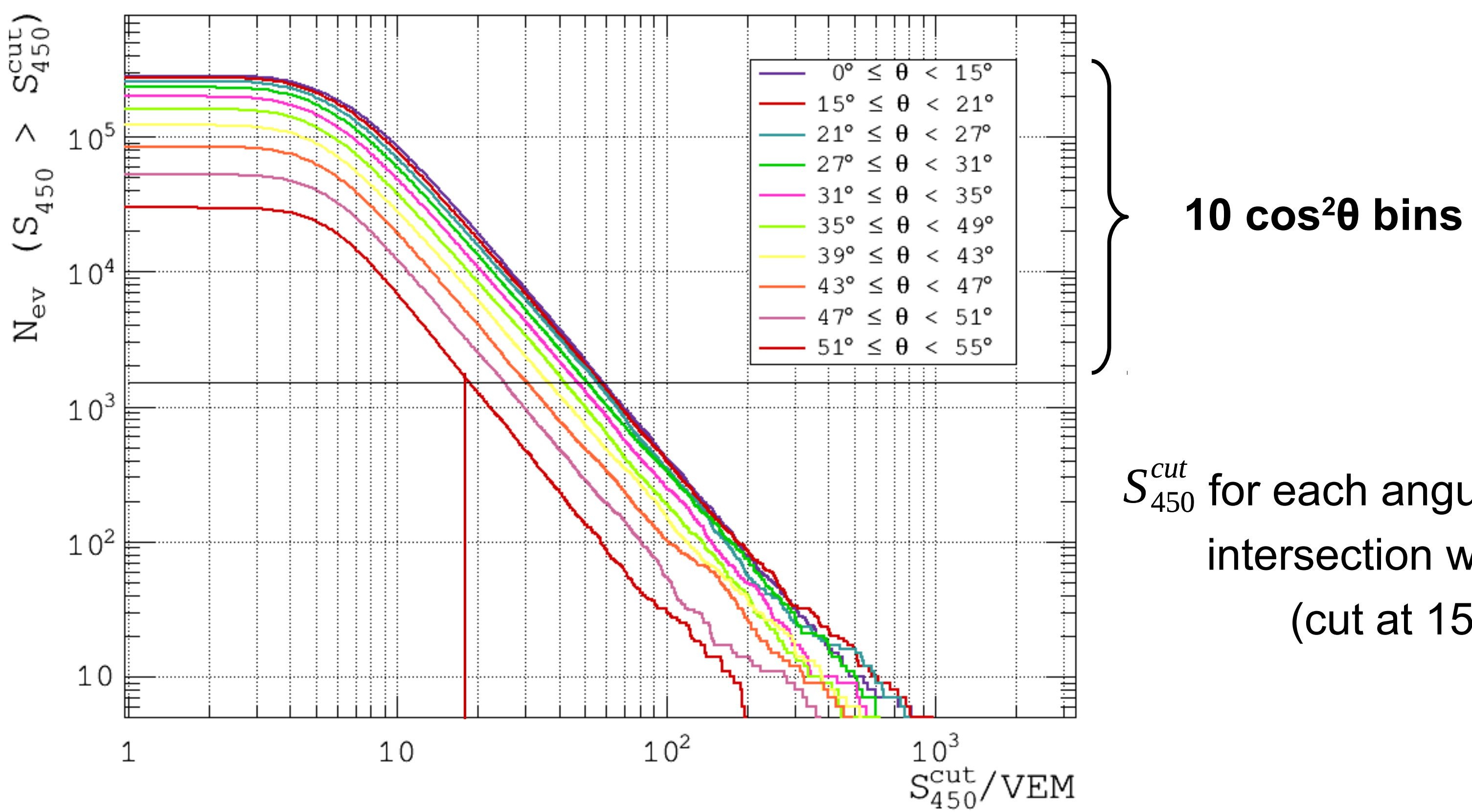
Constant Intensity Cut method

The **attenuation function CIC(θ)** is defined as third degree polynomial :

$$CIC(\theta)=1+a\cdot x(\theta)+b\cdot x^2(\theta)c\cdot x^3(\theta) \qquad x=\cos(\theta)^2-\cos(\theta_{ref})^2 \qquad \theta_{ref}=35°$$

- Events divided in **10 cos²θ bins** of equal size
- A cut at **1500 events** is chosen ⟶ S_{450}^{cut} : 1500 events with $S_{450} > S_{450}^{cut}$ in that bin

Integral event distributions :



S_{450}^{cut} for each angular bin is given by the intersection with the black line (cut at 1500 events)

Constant Intensity Cut method

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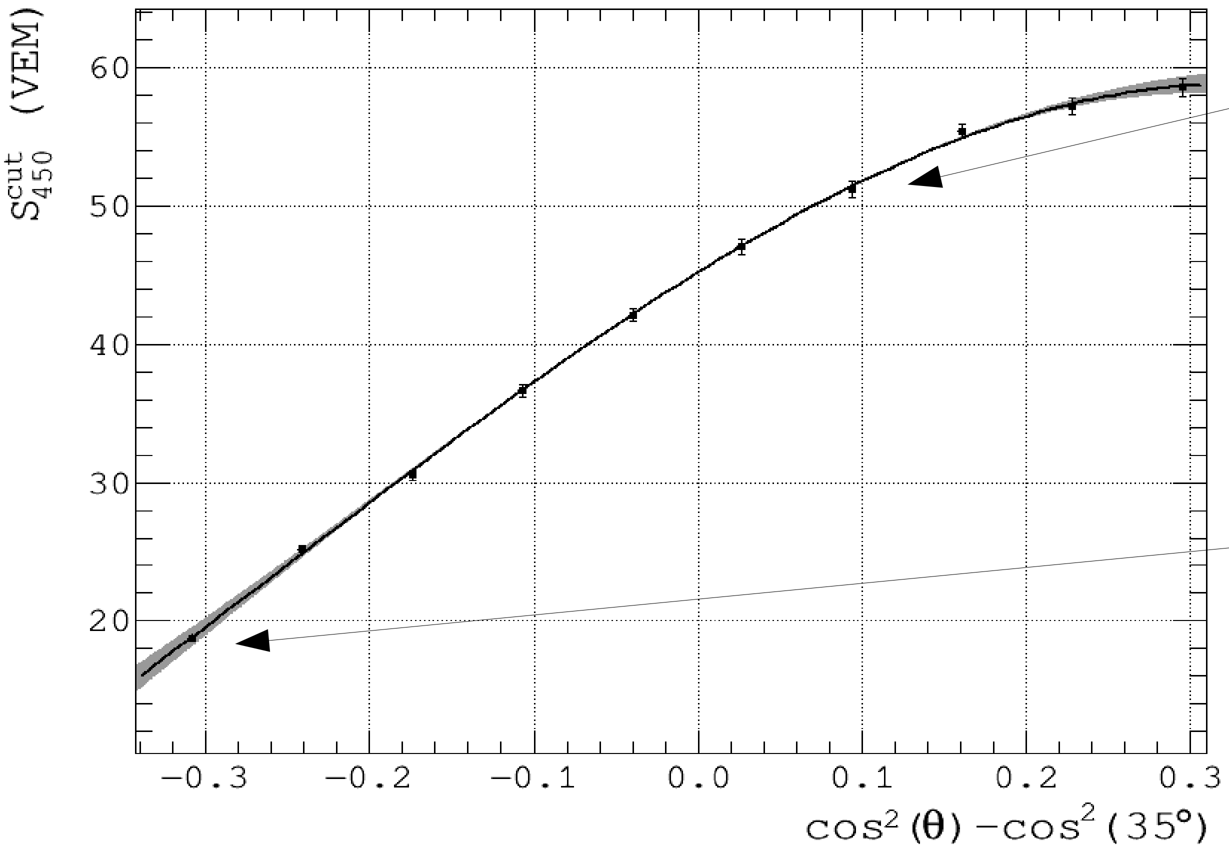
- Events divided in **10 $\cos^2\theta$ bins** of equal size
- A cut at **1500 events** is chosen ⟶ S_{450}^{cut} : 1500 events with $S_{450} > S_{450}^{cut}$ in that bin



- Errors on S_{450}^{cut} in each bin obtained with the **bootstrap method**
- The CIC **fit is performed** to estimate the parameters:

$$S_{450}^{cut}(\theta)=S_{35}^{cut}\cdot CIC(\theta)$$

$$S_{35}^{cut}, a, b, c$$

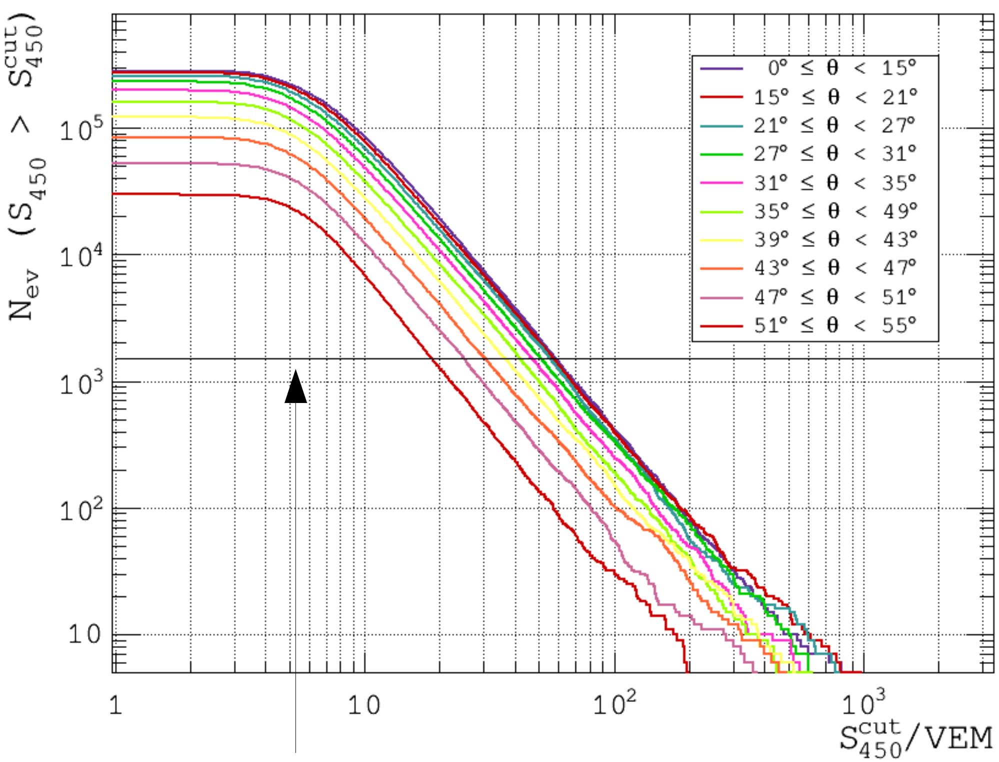
- **1σ uncertainty** band from the fit covariance matrix
- CIC(θ) from the fit → **S_{35}** estimated for each event

Constant Intensity Cut method

Estimated parameters:

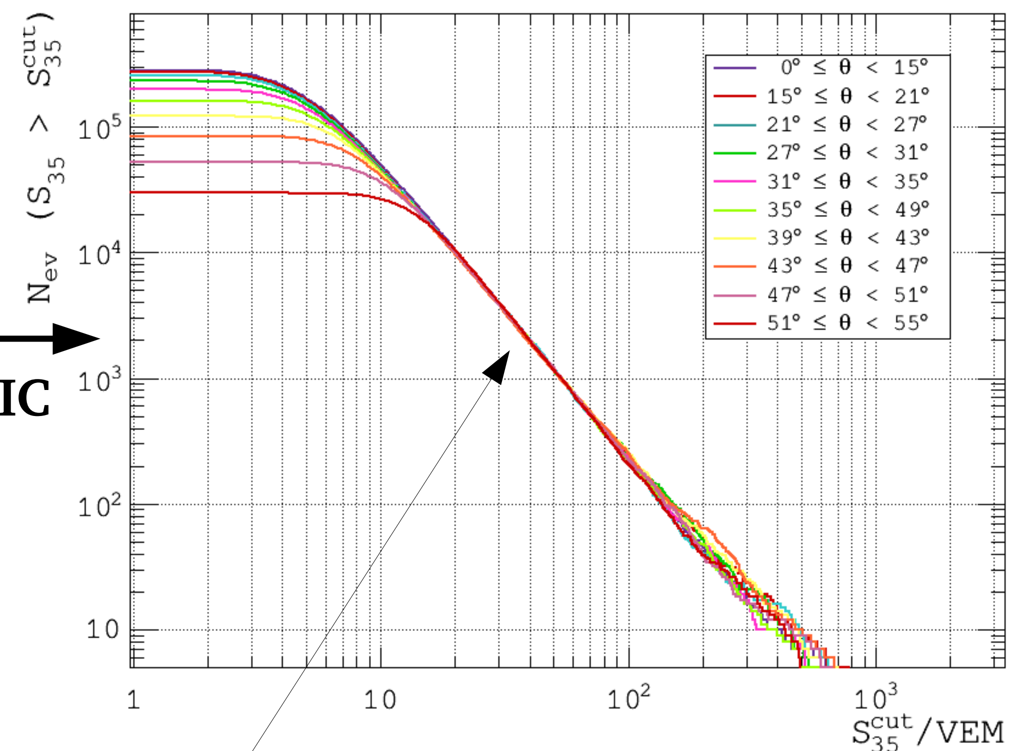
a	1.62 ± 0.04
b	-1.486 ± 0.103
c	-2.0 ± 0.5
S_{35}^{cut}	(45.2 ± 0.2) VEM
χ^2/ν	0.69

S_{450}^{cut}



CIC →

S_{35}^{cut}



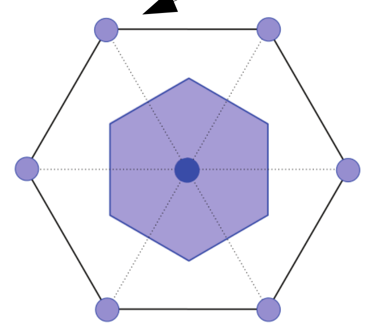
Cut at 1500 events

Superimposed curves → no θ dependence

Measurement of the energy spectrum

Geometrical exposure

Above the energy threshold of full trigger efficiency ($3 \cdot 10^{17}$ eV):



- **Hexagonal cell area** (d=750 m) :

$$A = \frac{\sqrt{3}}{2} d^2$$

- Selection of events with zenith angle between 0° and 55° :

$$\Omega = \int_0^{2\pi} d\phi \int_{0°}^{55°} d\theta \cos(\theta) \sin(\theta)$$

- Effective cell area:

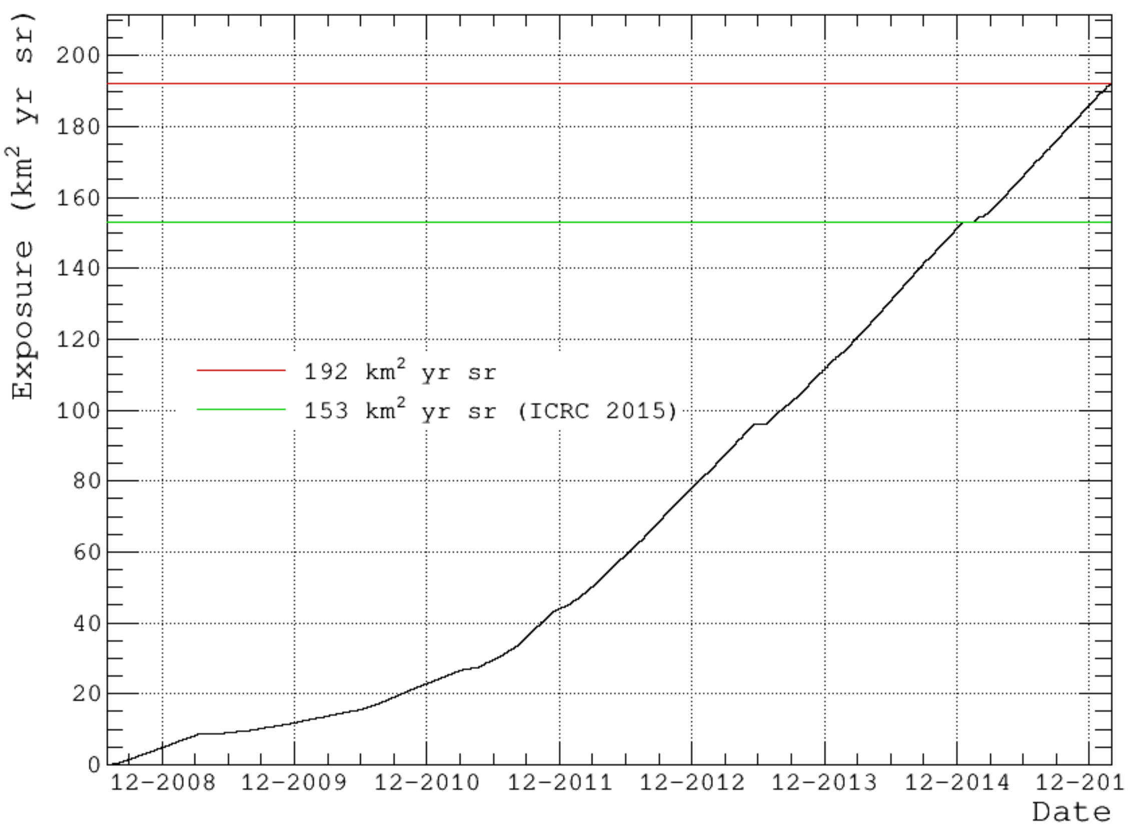
$$A_{6T5} = A \cdot \Omega = 1.02375\ km^2 \cdot sr$$

- Integrating over time :

$$\Sigma = \int dt\ A_{6T5} \cdot N(t)$$

→ **Total exposure:**

$$(192 \pm 6)\ km^2 \cdot sr \cdot yr$$



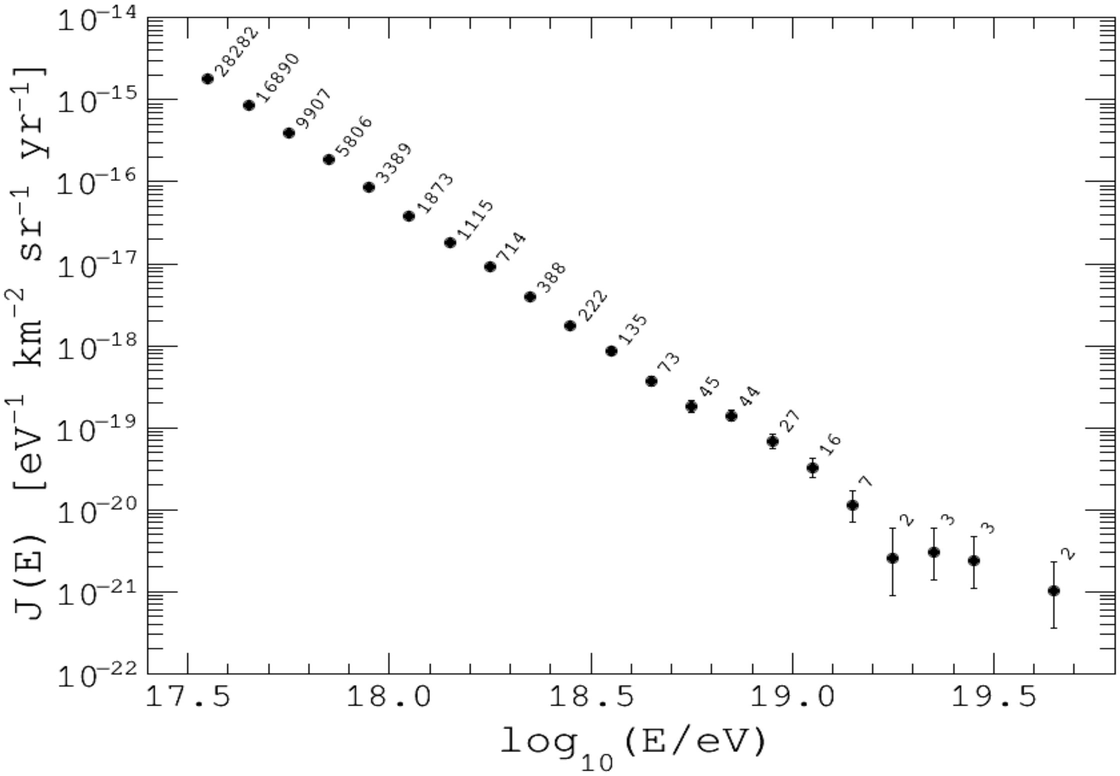
Observed energy spectrum

- Calibration : $S_{35} \longrightarrow$ **energy**

A= 12.87 · 10^{15} eV
B= 1.0128

[*The Pierre Auger Observatory: Contributions to the 34th International Cosmic Ray Conference (ICRC 2015)*]

$$J_{raw}(E) = \frac{dN}{\Sigma \cdot dlog_{10}(E)}$$



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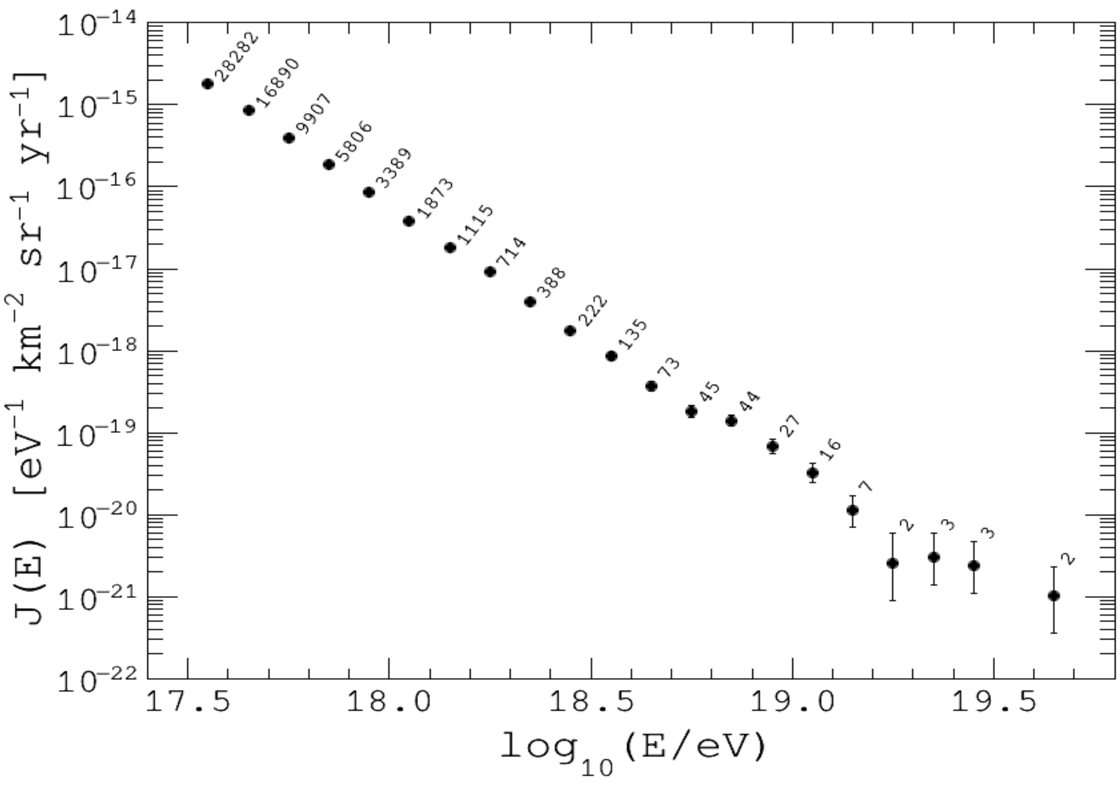

- Finite energy resolution σ(E)
- Steep power law

More events migrate from lower to higher energies than viceversa

Measured (raw) flux larger than true one

Unfolding procedure to obtain the unfolded flux

- Theoretical function: **Broken power law**

$$J_{unfol}^{theo}(E) = J_0 \left(\frac{E}{E_a}\right)^{-\gamma_1} \qquad E < E_a$$

$$J_{unfol}^{theo}(E) = J_0 \left(\frac{E}{E_a}\right)^{-\gamma_2} \qquad E > E_a$$

Unfolding procedure

Unfolding procedure to obtain the unfolded flux

$$J_{raw}(E') \xrightarrow{\text{fit}} J_{raw}^{theo}(E') \xrightarrow{\text{K}} J_{unfol}^{theo}(E) \xrightarrow{\text{C(E)}} J_{unfol}(E)$$

Unfolding procedure

Unfolding procedure to obtain the unfolded flux

$$J_{raw}(E') \xrightarrow{\text{fit}} J^{theo}_{raw}(E') \xrightarrow{K} J^{theo}_{unfol}(E) \xrightarrow{C(E)} J_{unfol}(E)$$

Migration matrix :

$$K(E,E',\sigma(E),\epsilon(E)) = \frac{1}{\sqrt{2\pi}\sigma(E)} \cdot \exp\left(-\frac{1}{2}\left(\frac{E'-E}{\sigma(E)}\right)^2\right) \cdot \epsilon(E)$$

$$J^{theo}_{raw}(E') = \int dE\, K(E,E',\sigma(E),\epsilon(E),bias(E)) \cdot J^{theo}_{unfol}(E)$$

Unfolding procedure

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$$J^{theo}_{raw}(E') = \int dE\, K(E,E',\sigma(E),\epsilon(E),bias(E)) \cdot J^{theo}_{unfol}(E)$$

- **Fit of J_{raw}** → Parameters that minimize $-\log(L) = \sum_i \mu_i - n_i \log \mu_i$

Bin i: n_i observed number of events

μ_i expected number of events in $J^{theo}_{raw}(E')$ } Obtained inserting parameters in $J^{theo}_{unfol}(E)$ and using K

→ $J^{theo}_{raw}(E')$ $J^{theo}_{unfol}(E)$

Unfolding procedure

Unfolding procedure to obtain the unfolded flux

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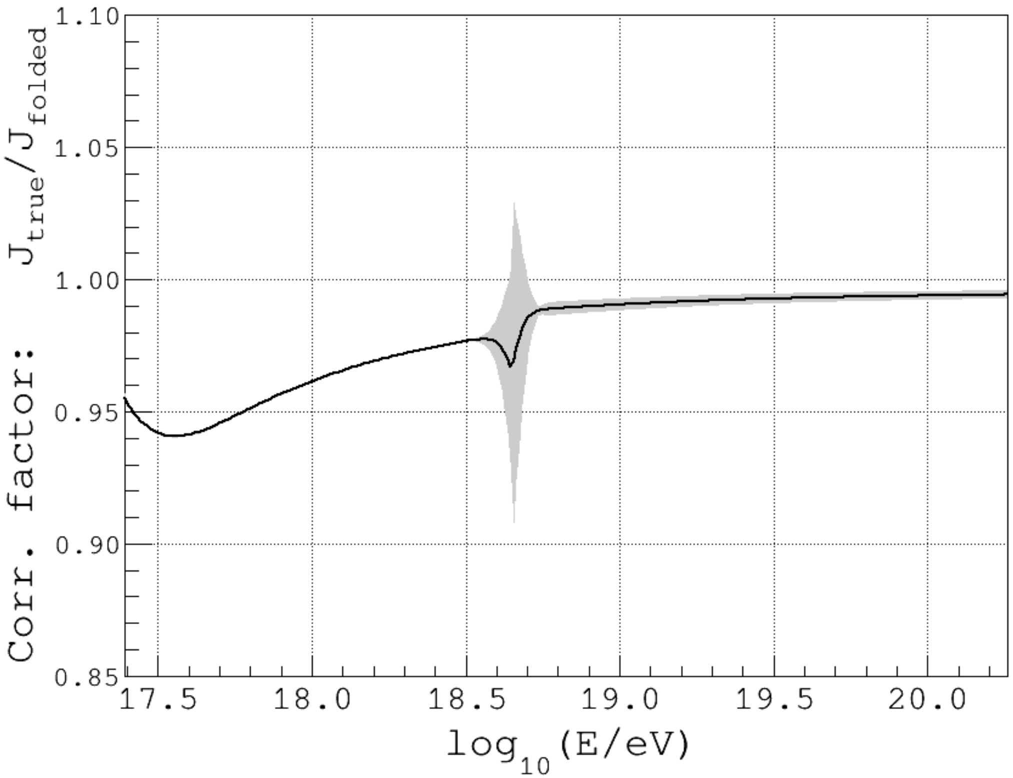
→ $J^{theo}_{raw}(E')$ $J^{theo}_{unfol}(E)$

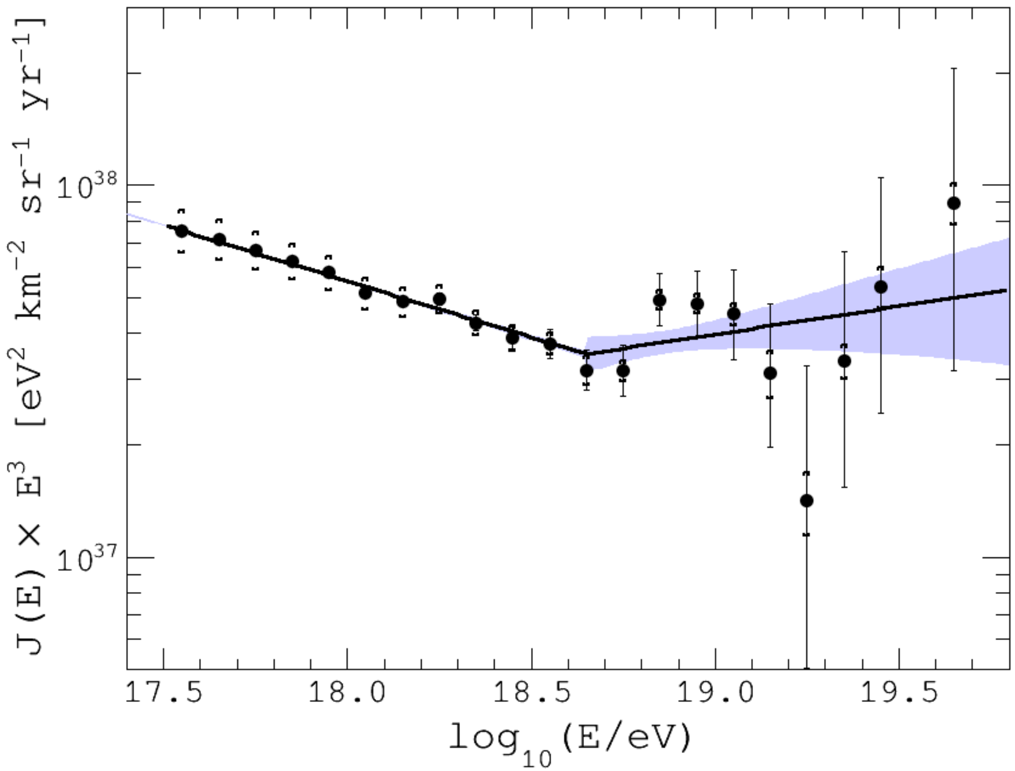
- **Correction factor**: $C(E) = \frac{J^{theo}_{unfol}(E)}{J^{theo}_{raw}(E')} = \frac{J_{unfol}(E)}{J_{raw}(E')}$ → $J_{unfol}(E)$

Unfolded spectrum

Correction factor : $C(E) = \frac{J_{unfol}(E)}{J_{raw}(E')}$



Unfolded spectrum:



Estimated parameters for the unfolded spectrum:

J_0	18.4 ± 0.3
$\log_{10}(E_a/eV)$	$18.65^{+0.08}_{-0.09}$
γ_1	3.30 ± 0.01
γ_2	$2.85^{+0.14}_{-0.15}$

Systematic uncertainties

Energy dependent uncertainties:

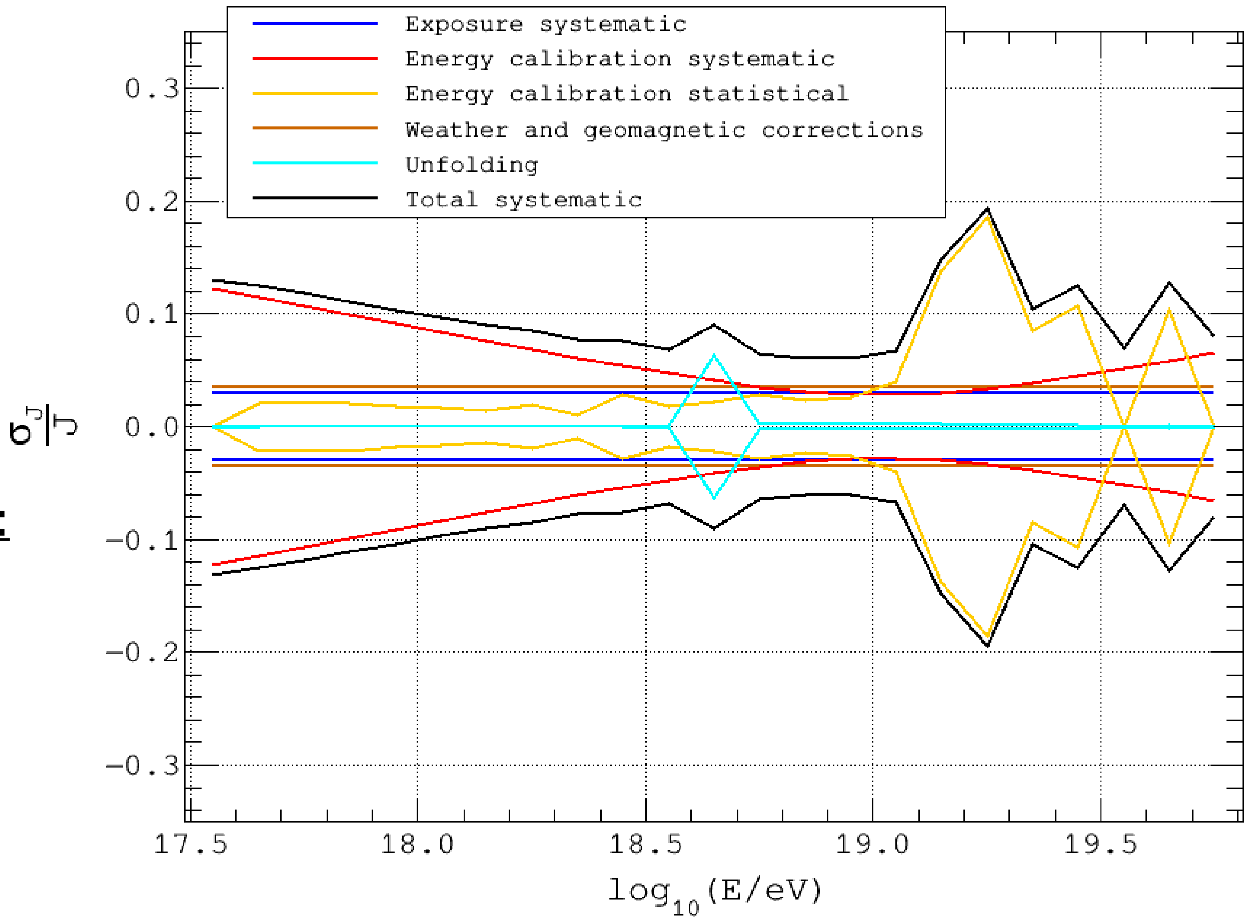
- **Systematic from unfolding correction :**

  the uncertainty on the correction factor C(E) propagates to the unfolded flux

$$J_{unfol}(E) = J_{raw}(E') \times C(E)$$

- **Statistical and systematic uncertainties from calibration :**
  - From energy bias
  - From comparison with an alternative calibration function

  [A. Schulz. for the Pierre Auger Collaboration, Internal note 2016]



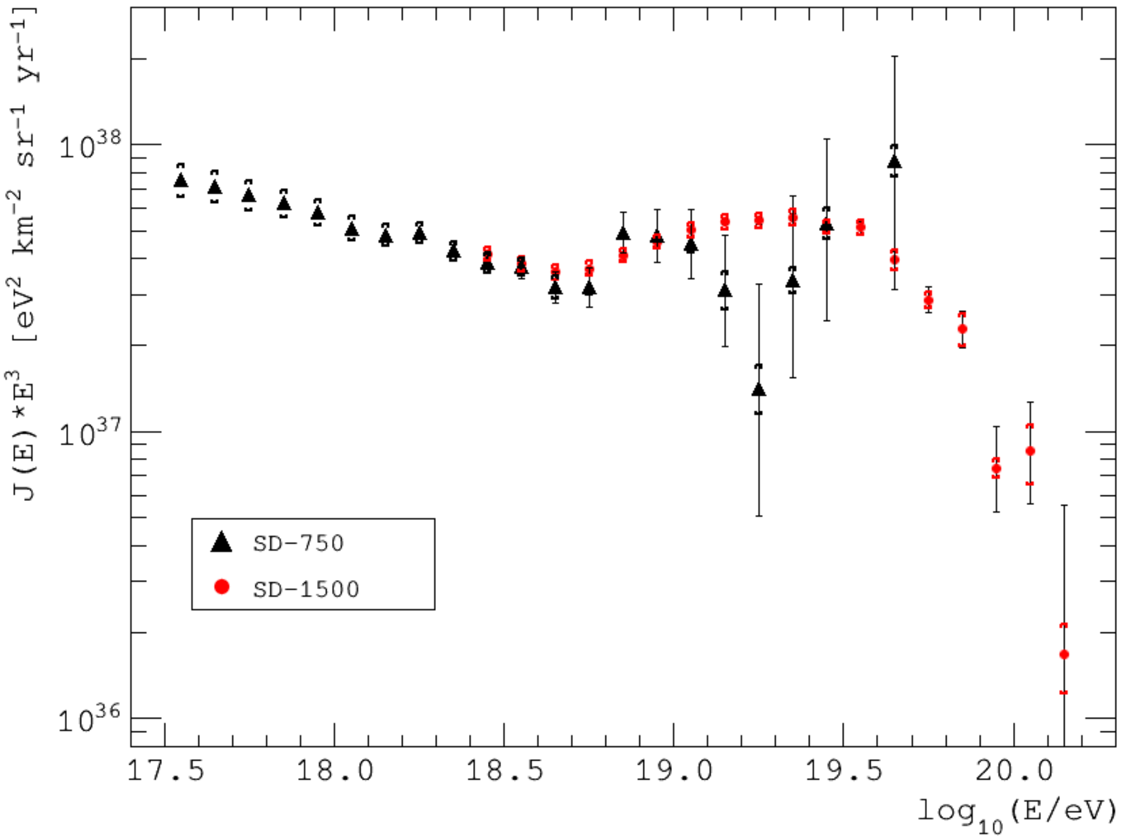
Energy independent uncertainties:

- **Systematic from exposure : 3%**
- **Systematic from weather and geomagnetic corrections : 3.5%**

Quadratic sum :

Total systematic uncertainty

Vertical spectrum

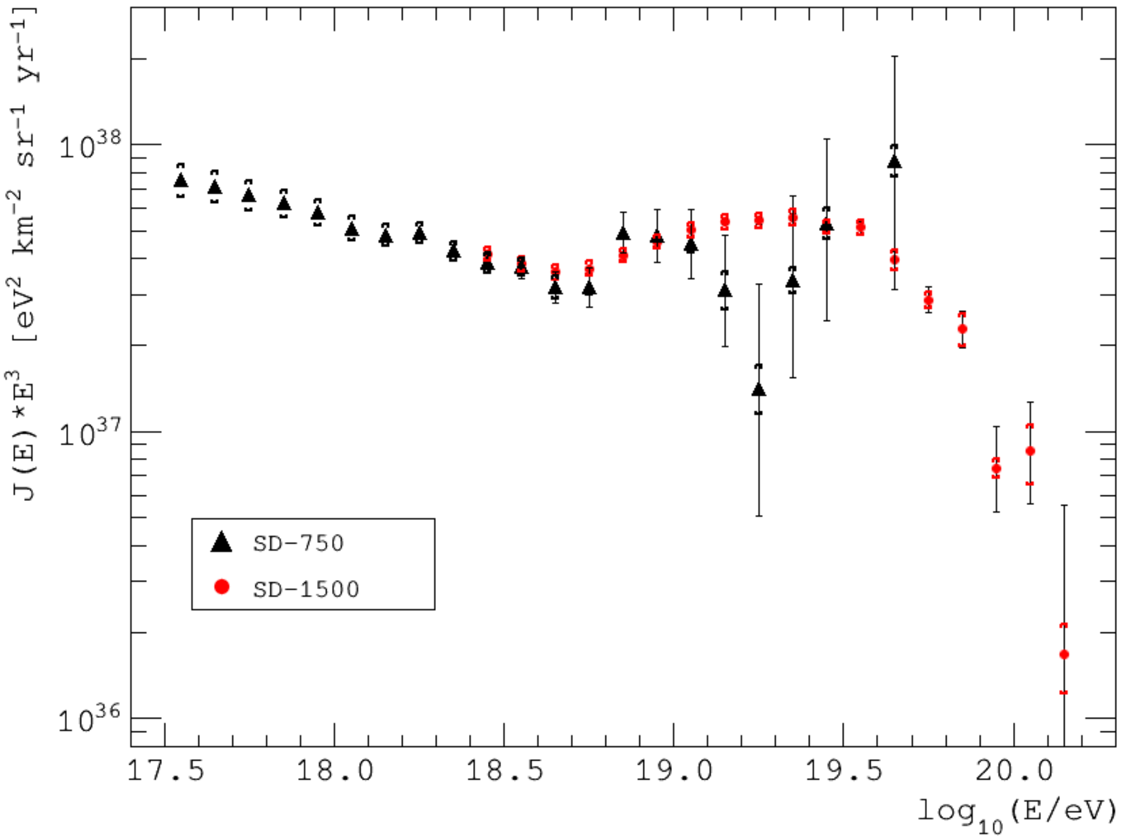


- **Data from SD-1500** (main array)
- Collected between January 2004 and February 2016
- $E > 3 \cdot 10^{18}$ eV , $\theta < 60°$
- Good statistics at the highest energies
- **Exposure**:

$$(48000 \pm 2000)\, km^2 \cdot sr \cdot yr$$

- **Systematic uncertainties**:
  - 5% from exposure
  - 3.5% from weather and geomagnetic correction

Vertical spectrum



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- **Systematic uncertainties**:
  - 5% from exposure
  - 3.5% from weather and geomagnetic correction

Combination of the two spectrum measurements → Higher quality description below and above the ankle

Fit function :

Broken power law with a smooth suppression at high energies

$$J(E) = J_0 \left(\frac{E}{E_a}\right)^{-\gamma_1} \qquad E < E_a$$

$$J(E) = J_0 \left(\frac{E}{E_a}\right)^{-\gamma_2} \left(1 + \left(\frac{E_a}{E_s}\right)^{\Delta\gamma}\right) \left(1 + \left(\frac{E}{E_s}\right)^{\Delta\gamma}\right)^{-1} \qquad E > E_a$$

Combination of vertical spectra

Maximimum likelihood method to take into account the statistical and systematic uncertainties

Likelihood to maximize:

$$L = \prod_{k=1}^{2} \prod_{i=1}^{N_k} \underbrace{L_k^{Norm}} \cdot \underbrace{L_{i,k}^{Poisson} \cdot L_{i,k}^{Nuisance}}$$

k=1 SD-750
k=2 SD-1500

$$L_k^{Norm} = \frac{1}{\sigma_k \sqrt{2\pi}} \cdot e^{-\frac{(a_k - 1)^2}{2\sigma_k^2}}$$

- σ_k → energy independent systematic errors
- a_k → normalization factor

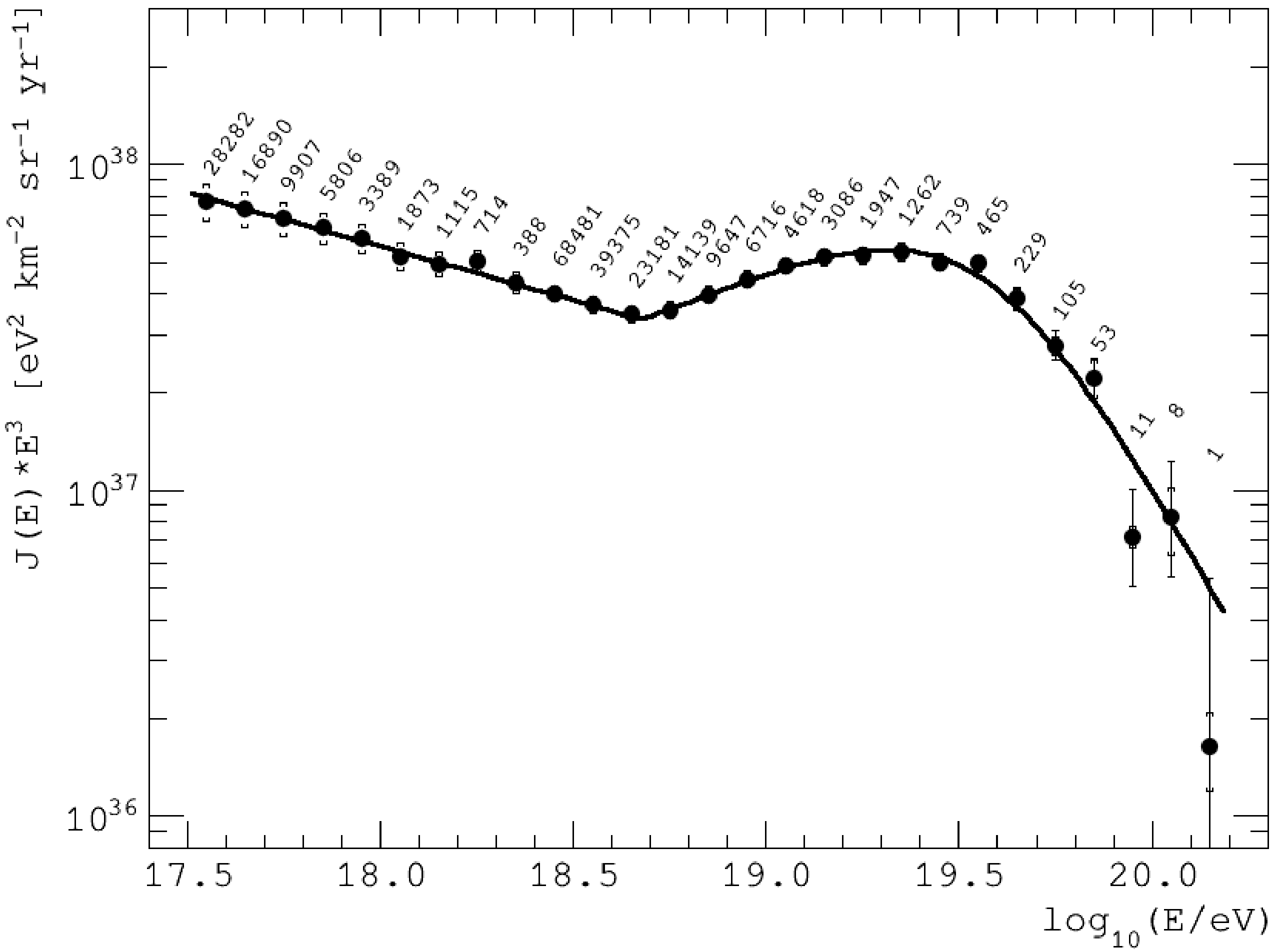
$$L_{ik}^{Poisson} = \frac{\nu_{ik}^{n_{ik}} \cdot e^{-\nu_{ik}}}{n_{ik}!}$$

- $\nu_{i,k}$ → nuisance parameters
- **$n_{i,k}$ → observed number of events**

$$L_{ik}^{Nuisance} = \frac{1}{\sigma_{ik} \sqrt{2\pi}} e^{-\frac{(\nu_{ik} - \mu_{ik})^2}{2\sigma_{ik}^2}}$$

- **$\mu_{i,k}$ → expected number of events**
- $\sigma_{i,k}$ → energy dependent systematic errors

Combined vertical spectrum



Estimated parameters for the combined spectrum:

J_0	18.52 ± 0.04
$\log_{10}(E_a/eV)$	18.68 ± 0.01
γ_1	3.33 ± 0.02
γ_2	2.53 ± 0.04
$\log_{10}(E_s/eV)$	19.57 ± 0.03
$\Delta\gamma$	2.6 ± 0.2
$a_{SD\text{-}750}$	0.98 ± 0.04
$a_{SD\text{-}1500}$	1.03 ± 0.04

- **Combined flux J** : weighted mean
- **Systematic uncertainty :** weighted mean
- **Statistical uncertainty :** propagation

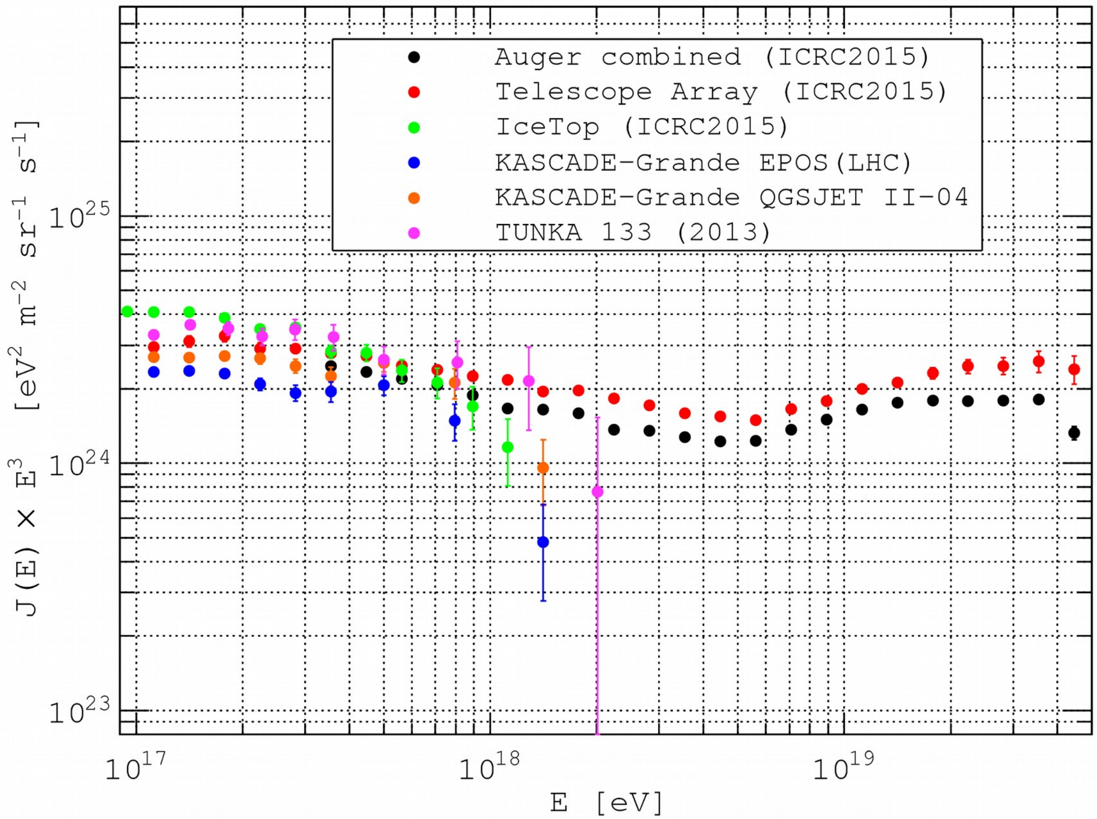
$$J(E) = J_0 \left(\frac{E}{E_a}\right)^{-\gamma_1} \qquad E < E_a$$

$$J(E) = J_0 \left(\frac{E}{E_a}\right)^{-\gamma_2} \left(1 + \left(\frac{E_a}{E_s}\right)^{\Delta\gamma}\right) \left(1 + \left(\frac{E}{E_s}\right)^{\Delta\gamma}\right)^{-1} \qquad E > E_a$$

Conclusions and prospects

- Infill spectrum reconstruction :
  - **Constant Intesity Cut** ***new***
  - Energy calibration ***parametrization already published***
  - **Unfolding** → unfolded spectrum ***new***
- **Combination of vertical spectra** taking into account the systematic uncertainties

→ energy spectrum **from 3 · 10^{17} eV to few 10^{20} eV**



- Describe the spectrum with a **function with a smooth change** of slope at the ankle energy
- Combination with the other data samples from Auger (**inclined and hybrid spectra**)
- **Comparison with other experimental results** (KG, IceTop, TA)

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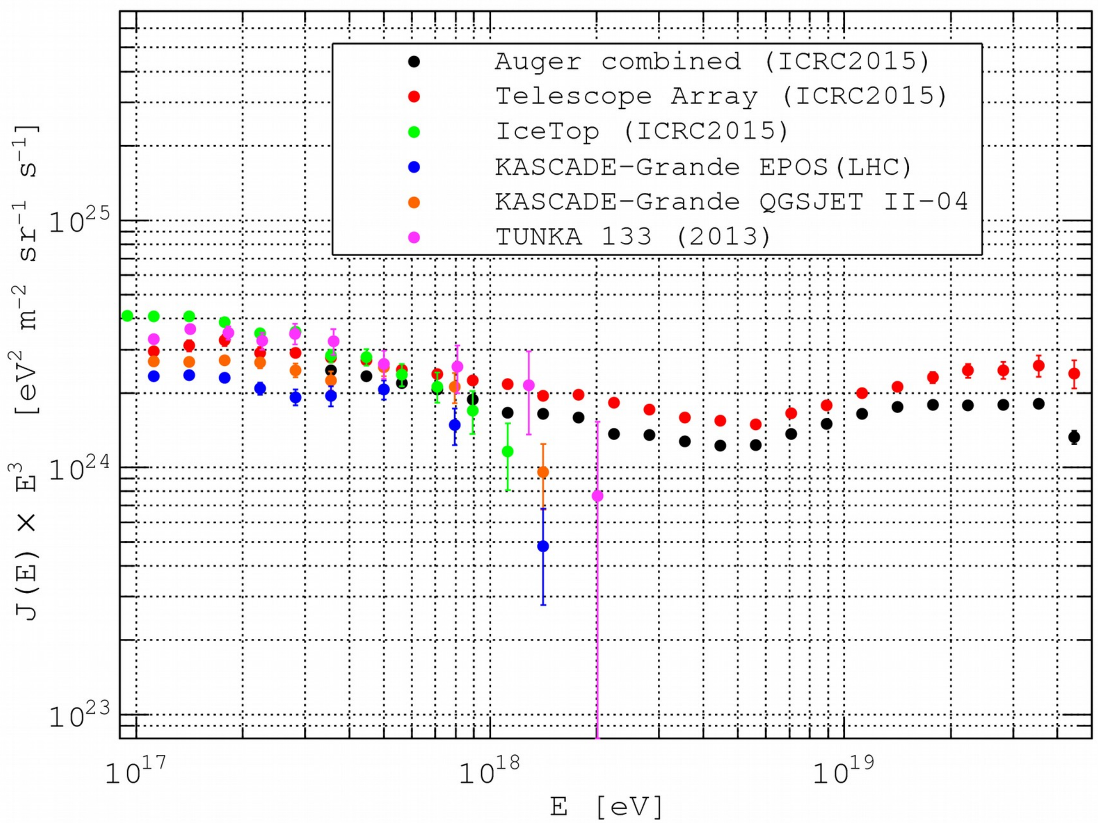

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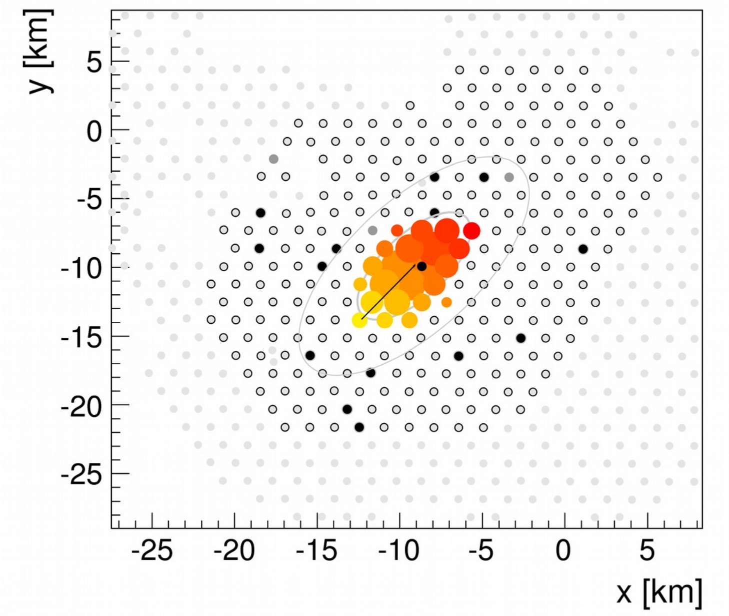
Grazie per l’attenzione

The Pierre Auger Observatory

Surface Detector (SD)

→ Estimation of **arrival direction**, **shower core position** and **shower size**

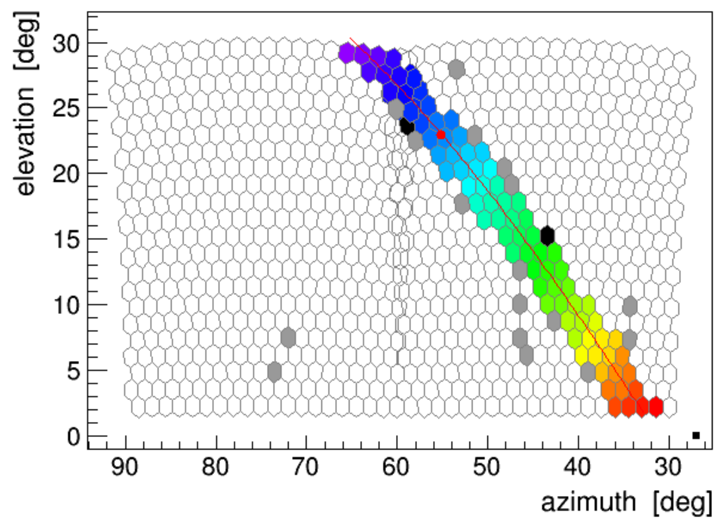
- Duty cycle of ~100 %
- SD calibration → signals expressed in VEM (Vertical Equivalent Muon)



Fluorescence Detector (FD)

→ Estimation of **calorimetric energy** and $\mathbf{X_{max}}$

- Duty cycle of ~15 % (clear and moonless nights)
- FD calibration : absolute and relative



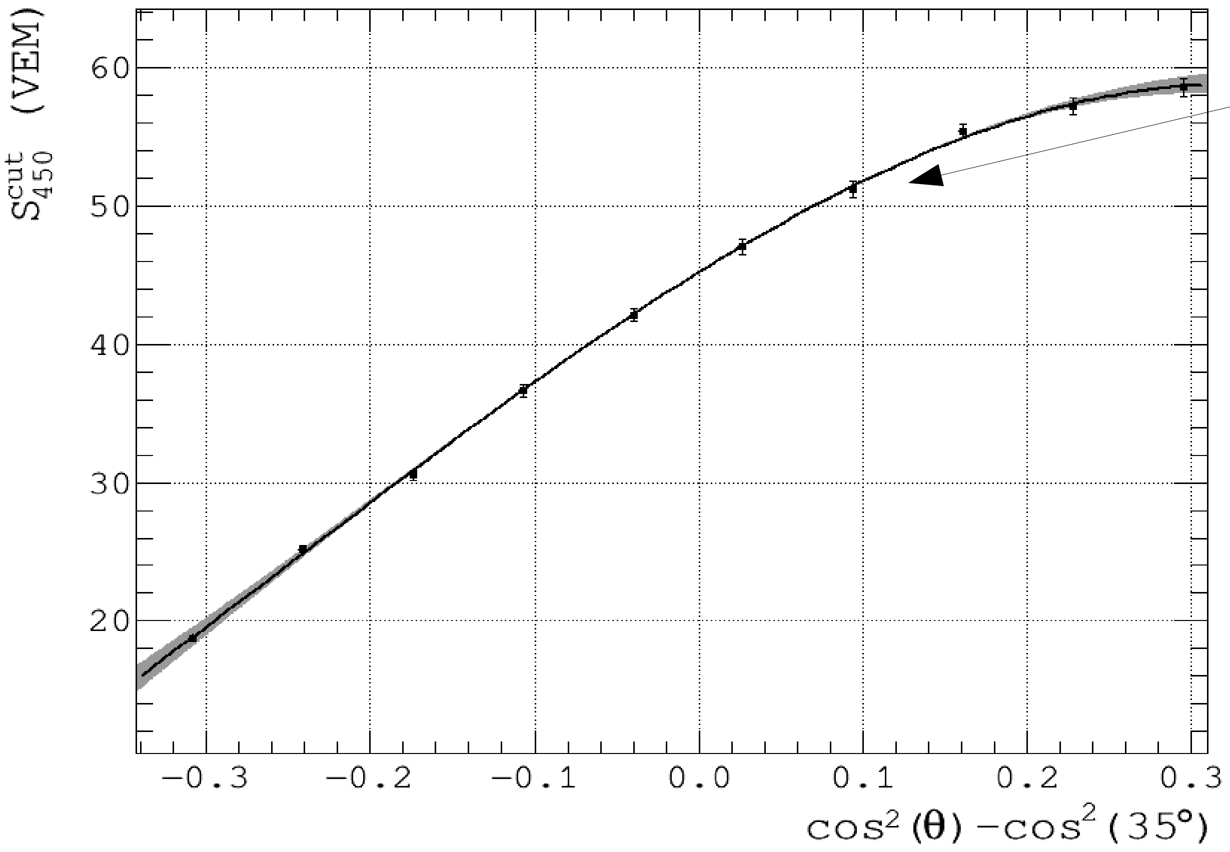
Hybrid events : those observed by both detectors

Constant Intensity Cut method

The **attenuation function CIC(θ)** is defined as third degree polynomial :

$$CIC(\theta)=1+a\cdot x(\theta)+b\cdot x^2(\theta)c\cdot x^3(\theta) \qquad x=\cos(\theta)^2-\cos(\theta_{ref})^2 \qquad \theta_{ref}=35°$$

- Events divided in **10 $\cos^2\theta$ bins** of equal size
- A cut at **1500 events** is chosen ⟶ S_{450}^{cut} : 1500 events with $S_{450} > S_{450}^{cut}$ in that bin



Errors on S_{450}^{cut} in each bin obtained with the **bootstrap method**

- Values of S_{450} drawn from the measured distribution
- **500 simulated samples** of S_{450}
- Cut at 1500 events for each sample → 500 S_{450}^{cut} values
- Variance S_{450}^{cut} distribution

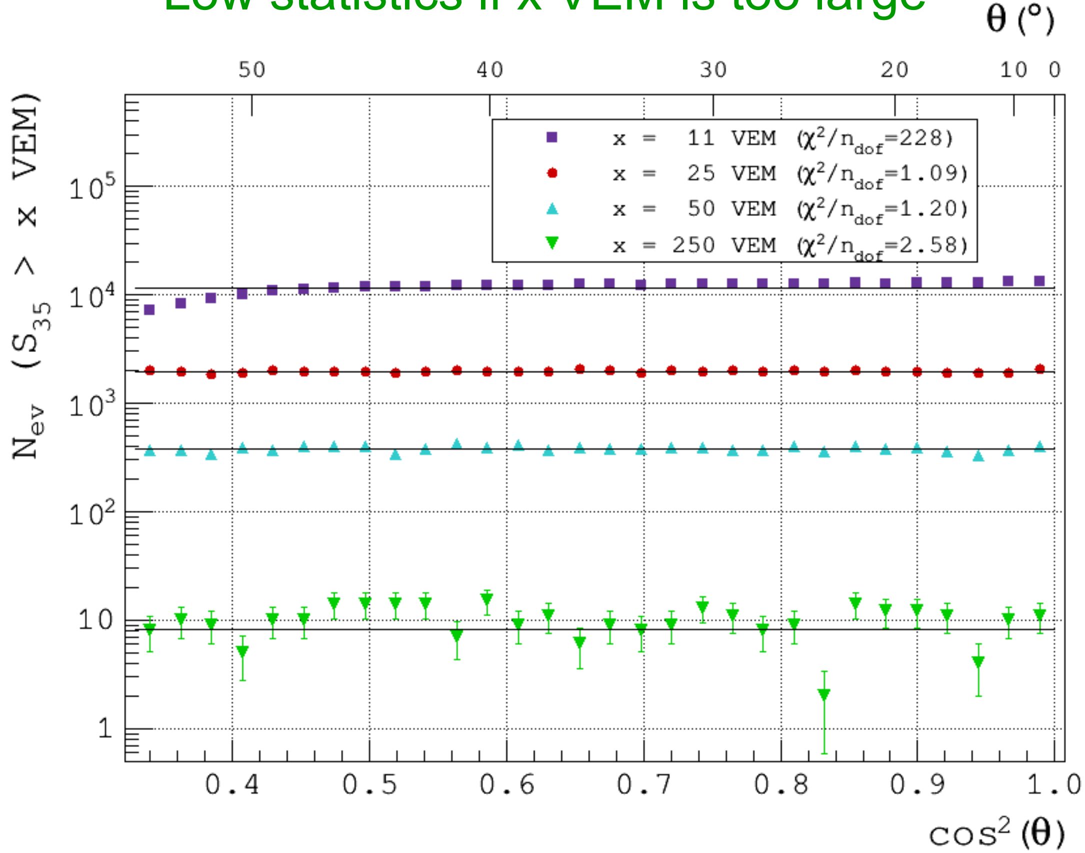
Constant Intensity Cut method

The $\cos^2\theta$ distribution is **uniform** selecting events above any $S_{35} > S_{35}^{cut}$

S_{35}^{cut}= 22.4 VEM

(~full trigger efficiency threshold)

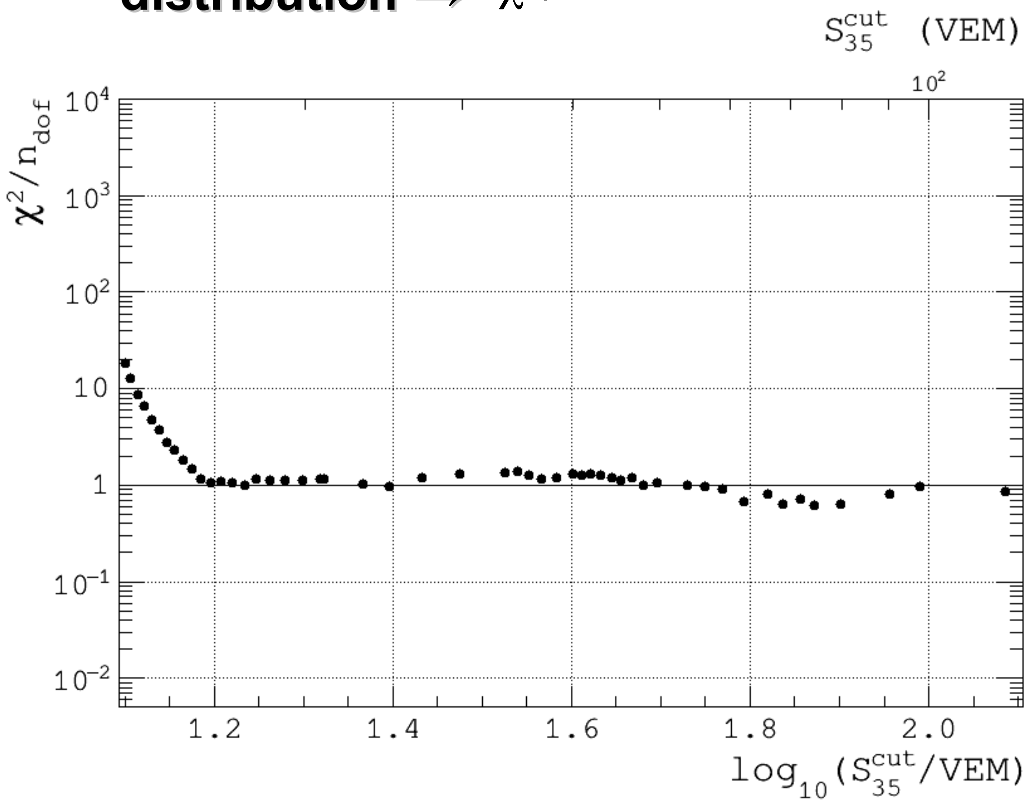
- Rising slope below the threshold
- Uniformity above above the threshold
- Low statistics if x VEM is too large



Constant Intensity Cut method

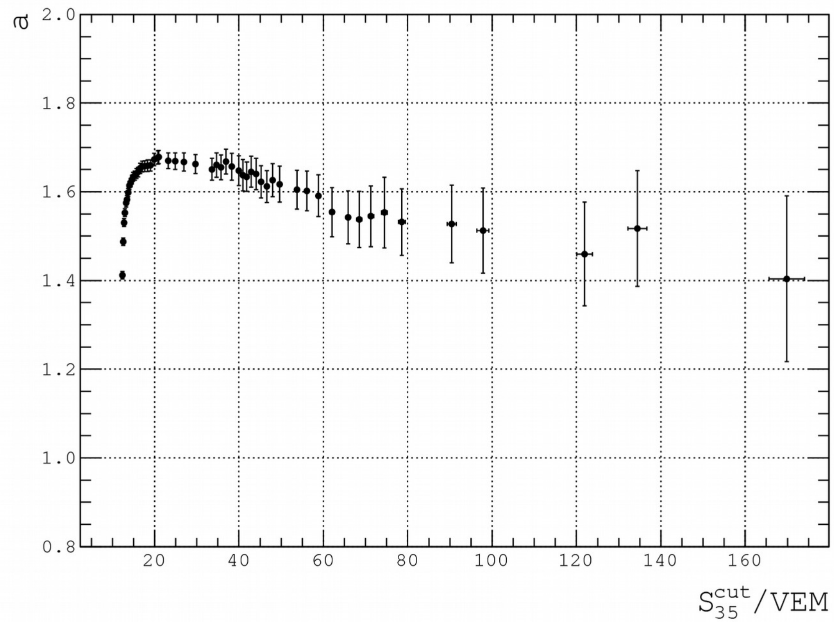
The $\cos^2\theta$ distribution is **uniform** selecting events above any $S_{35} > S_{35}^{cut}$

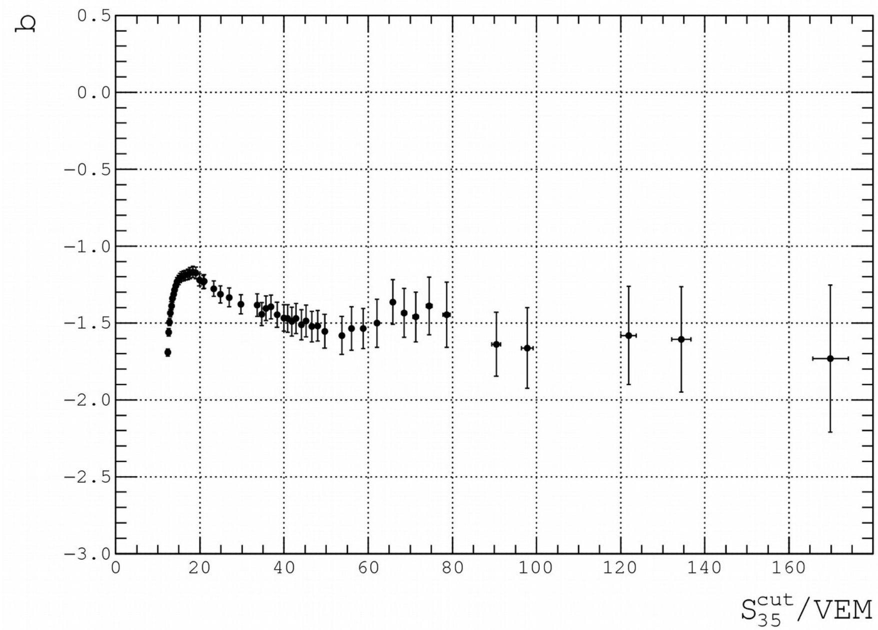
- CIC performed at different cut values on the number of events
  $\rightarrow$ different energy ($=S_{35}^{cut}$) values
- $\cos^2\theta$ distributions for selected events
- **A constant is fitted to each $\cos^2\theta$ distribution** $\rightarrow$ χ^2/ν

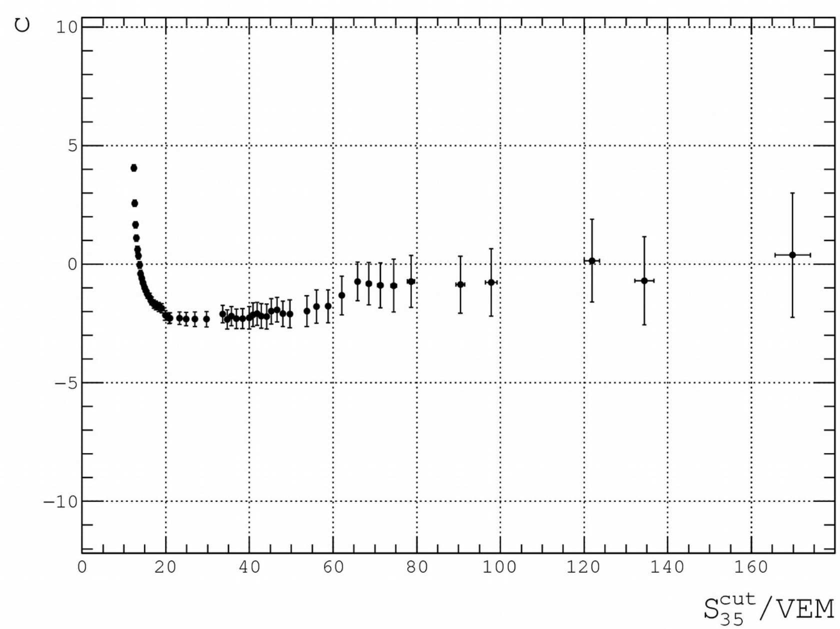


Constant Intensity Cut method

CIC parameters obtained with different cuts on the number of events (= S_{35}^{cut})







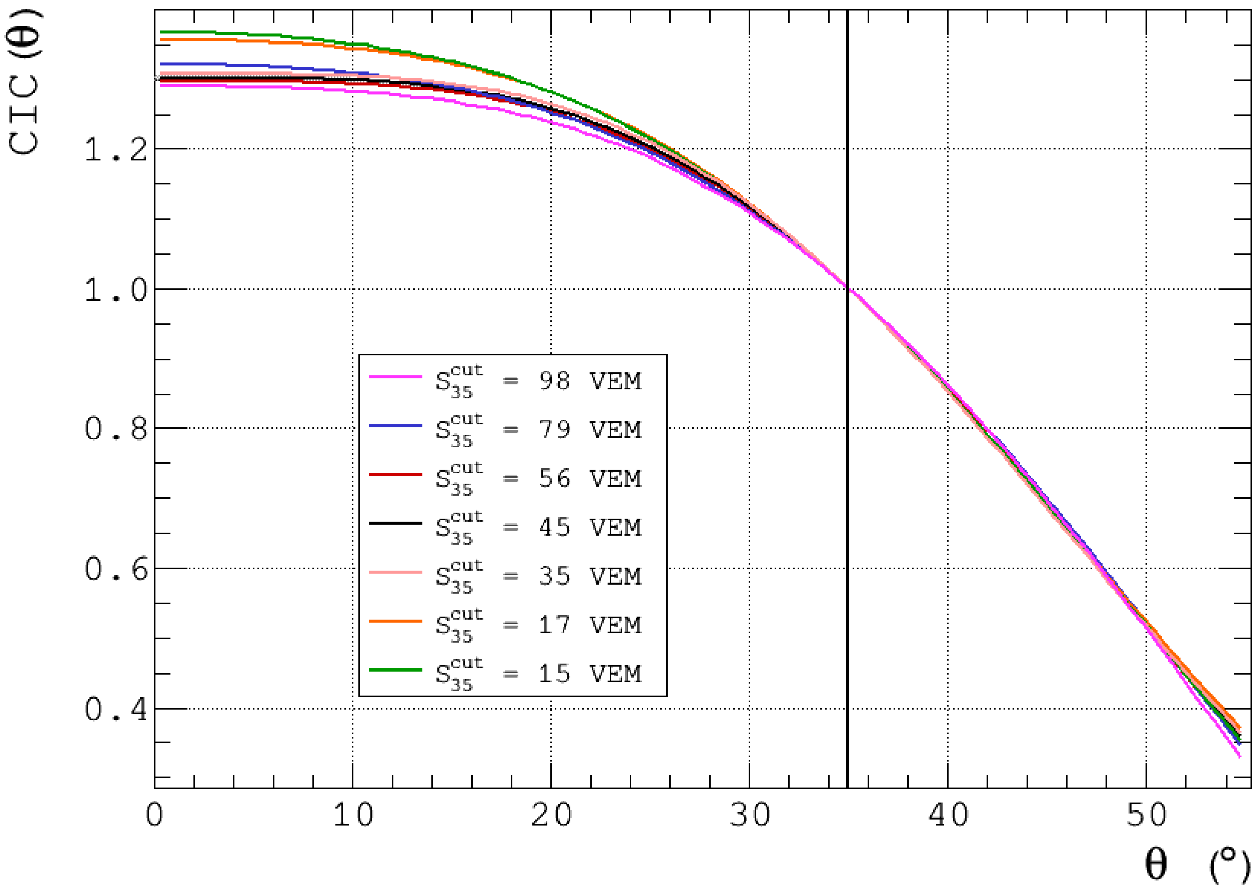
Estimated parameters of the CIC(θ) function for different S_{35}^{cut} values

↓

Smaller fluctuations above the full efficiency threshold

Constant Intensity Cut method

CIC parameters obtained with different cuts on the number of events (= S_{35}^{cut})



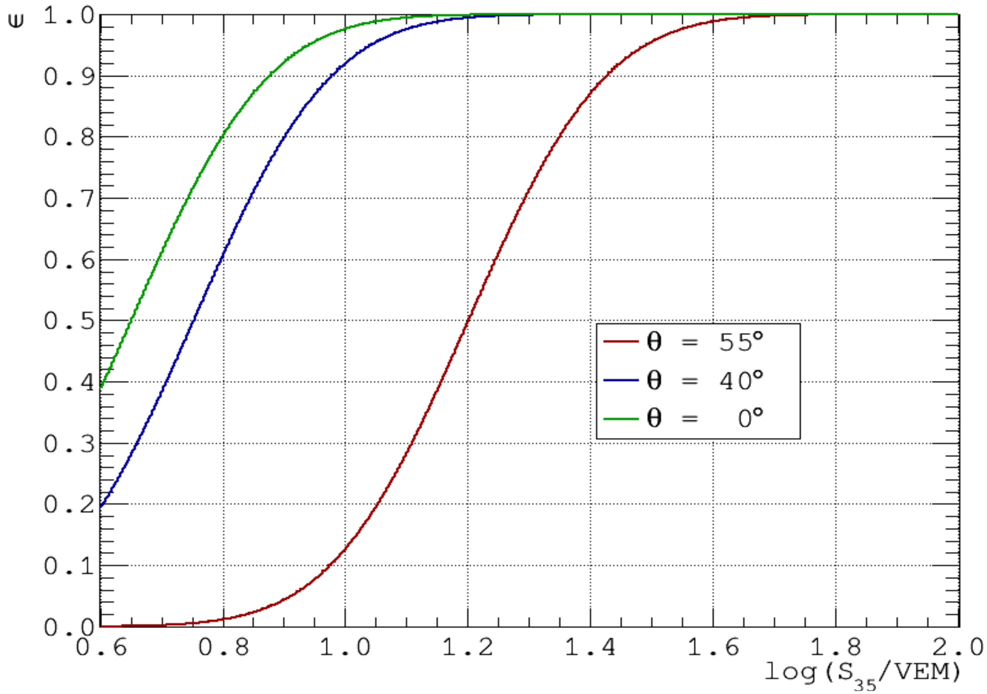
- Full trigger efficiency threshold: S_{35}^{cut}= 22 VEM
- **S_{35}^{cut}= 45 VEM** is the chosen cut

Above the threshold **NO large deviation from the one** obtained at 45 VEM

Migration matrix parameters

$$K(E,E',\sigma(E),\epsilon(E'),bias(E))=\frac{1}{\sqrt{2\pi}\sigma(E)}\cdot\exp\left(-\frac{1}{2}\left(\frac{E'-E}{\sigma(E)}\right)^2\right)\epsilon(E)$$

- **Trigger efficiency:** $\epsilon(S,\theta)=\frac{1}{2}\left(1+erf\left(\frac{logS-a(\theta)}{b}\right)\right)$ $\quad erf(y)=\frac{2}{\sqrt{\pi}}\int_0^y dx\, e^{\frac{-x^2}{2}}$



$$a(\theta)=a_0+a_1\cos^2(\theta)+a_2\cos^4(\theta)+a_3\cos^6(\theta)$$

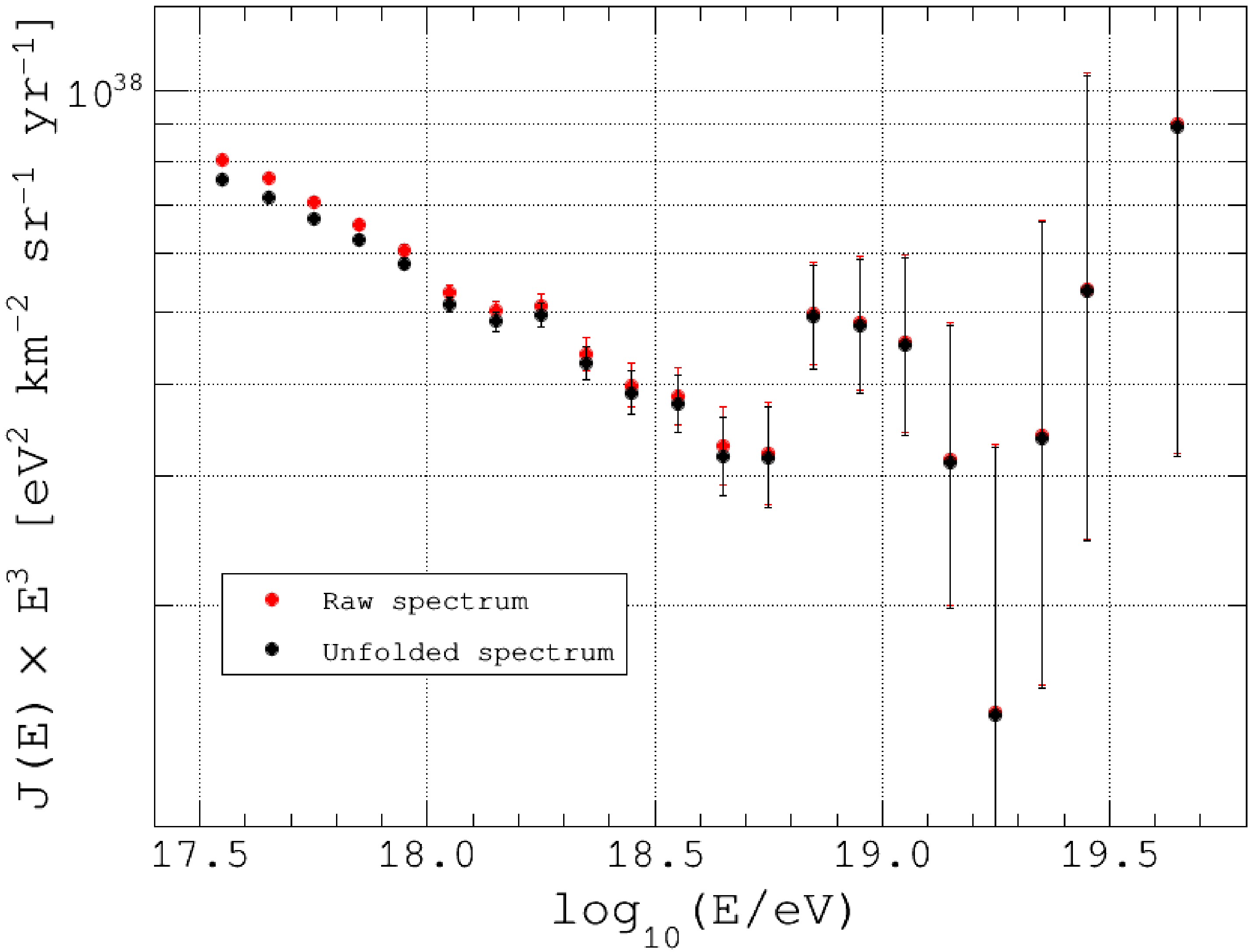
Parameters from simulations:

a_0	2.39 ± 0.06
a_1	-4.86 ± 0.32
a_2	4.10 ± 0.56
a_3	-0.98 ± 0.31
b	0.249 ± 0.004

- **Energy resolution:** QGSJET-II.04 simulations with a 50/50 mix of proton and iron primaries

$$\frac{\sigma(E)}{E}=0.078+0.165/\sqrt{\frac{E}{10^{17 eV}}}$$

Raw and unfolded spectra



Infill spectrum: plots of residuals

$$J_{theo}(E) = J_0\left(\frac{E}{E_a}\right)^{-\gamma_1} \qquad E < E_a$$

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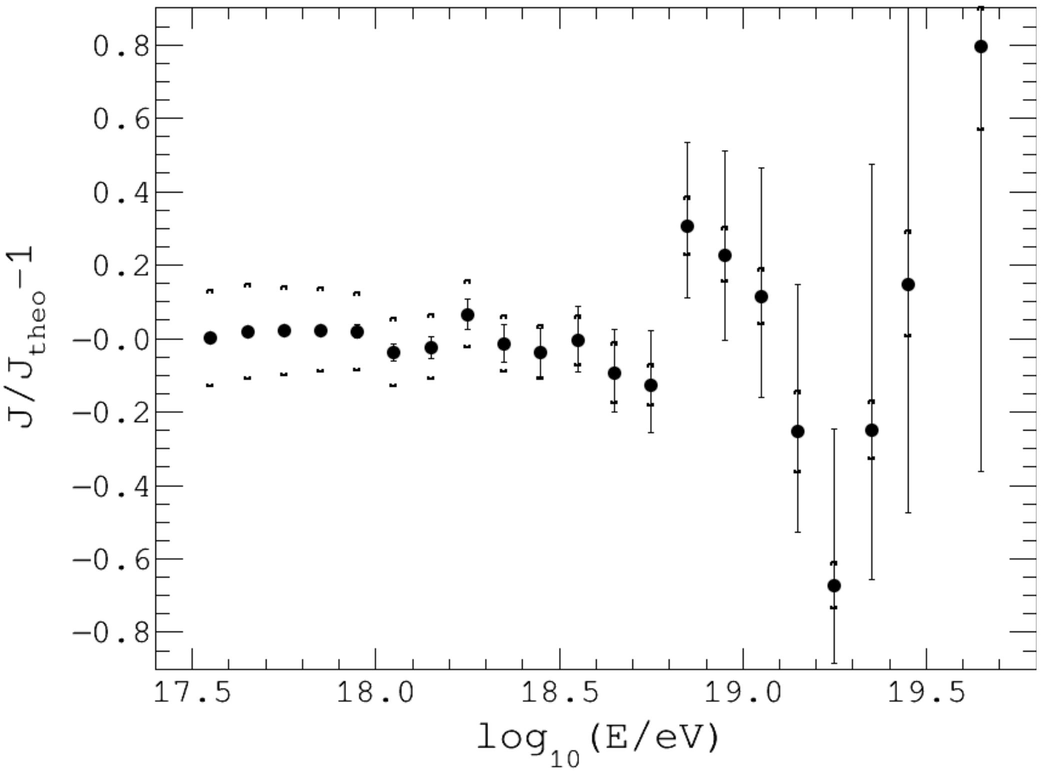
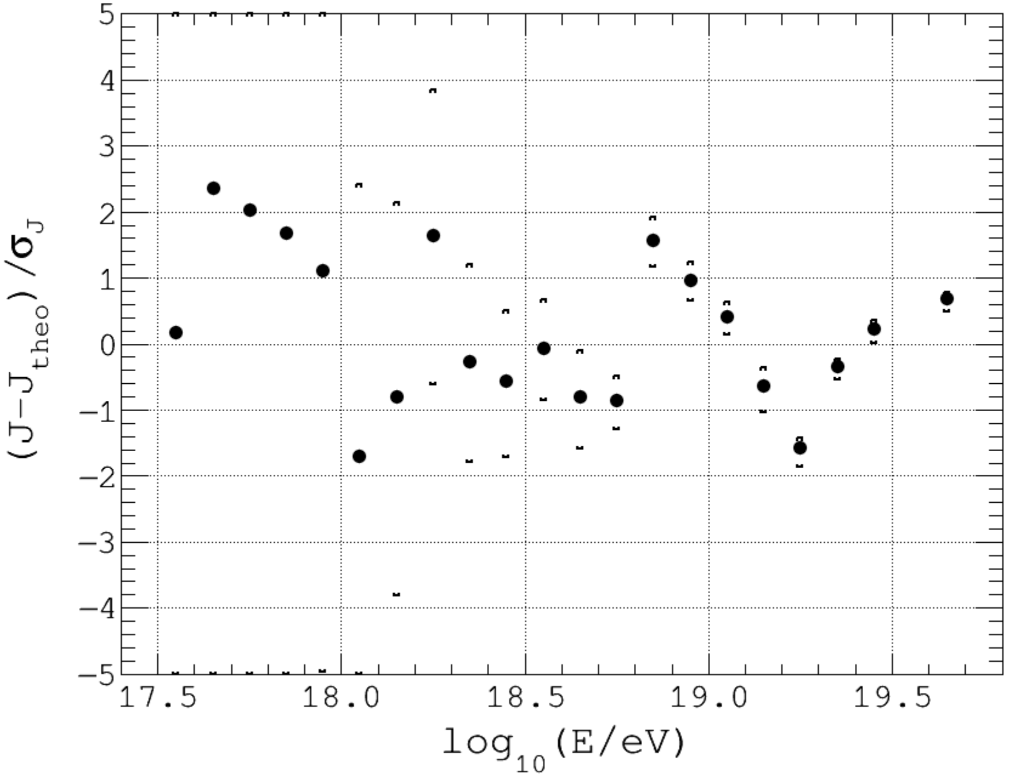
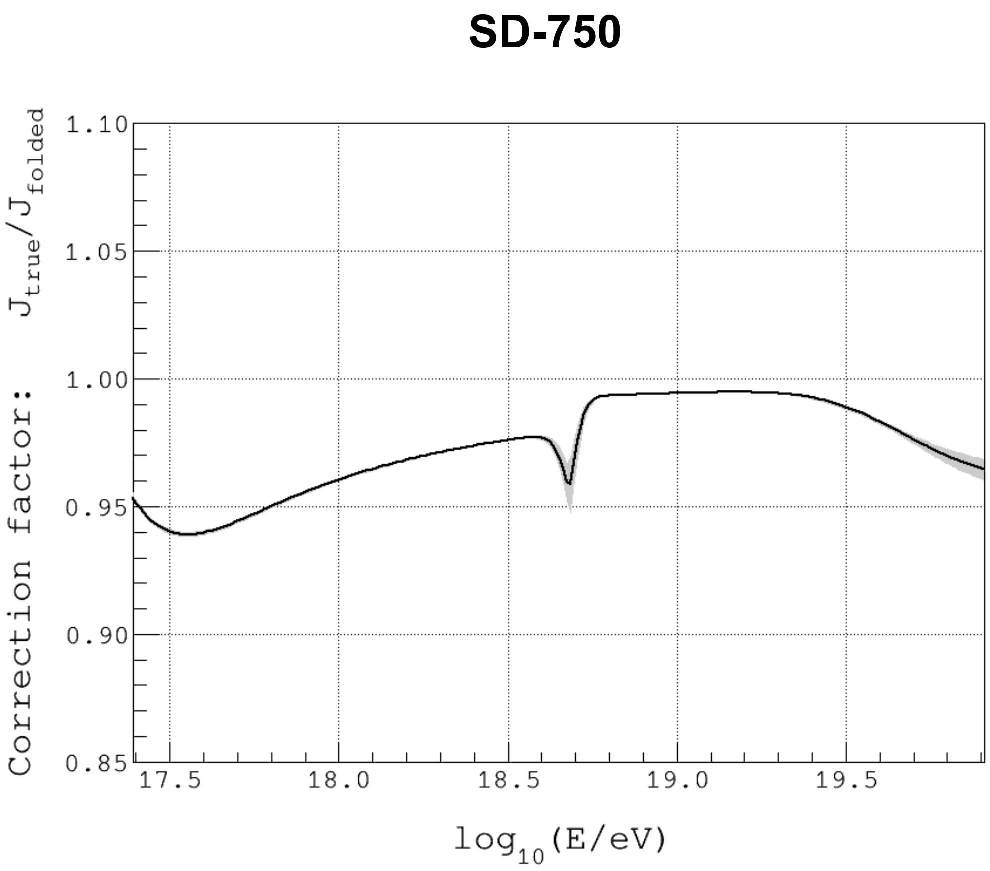
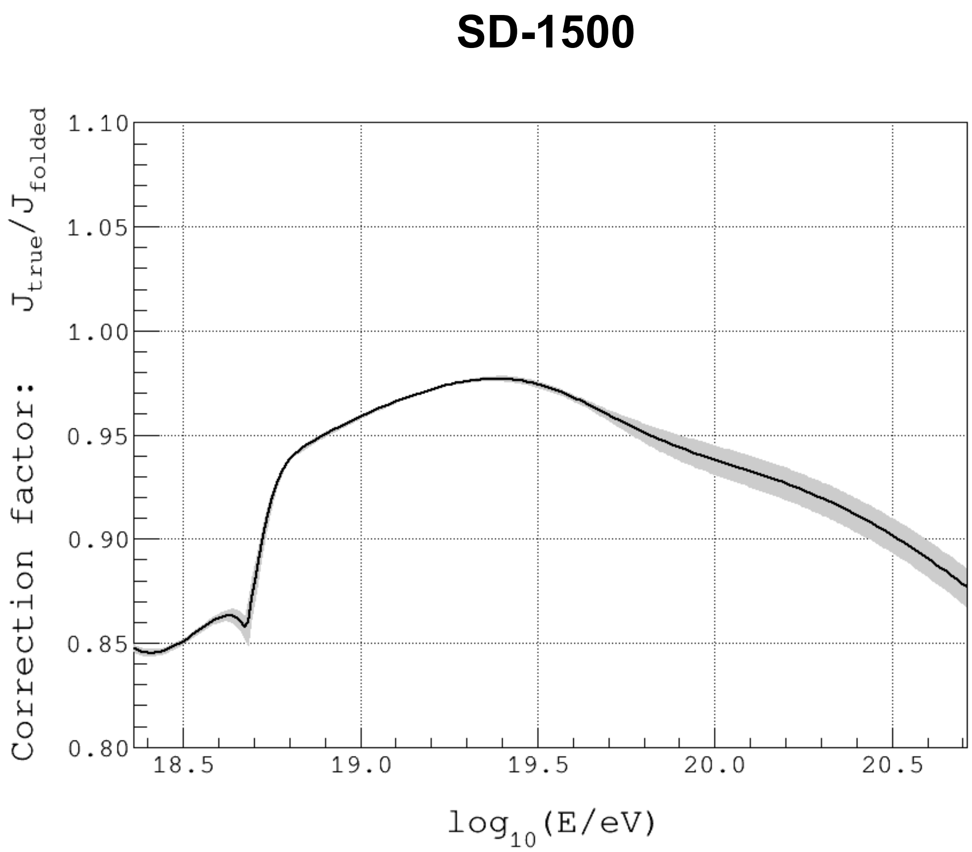




Unfolding correction factors





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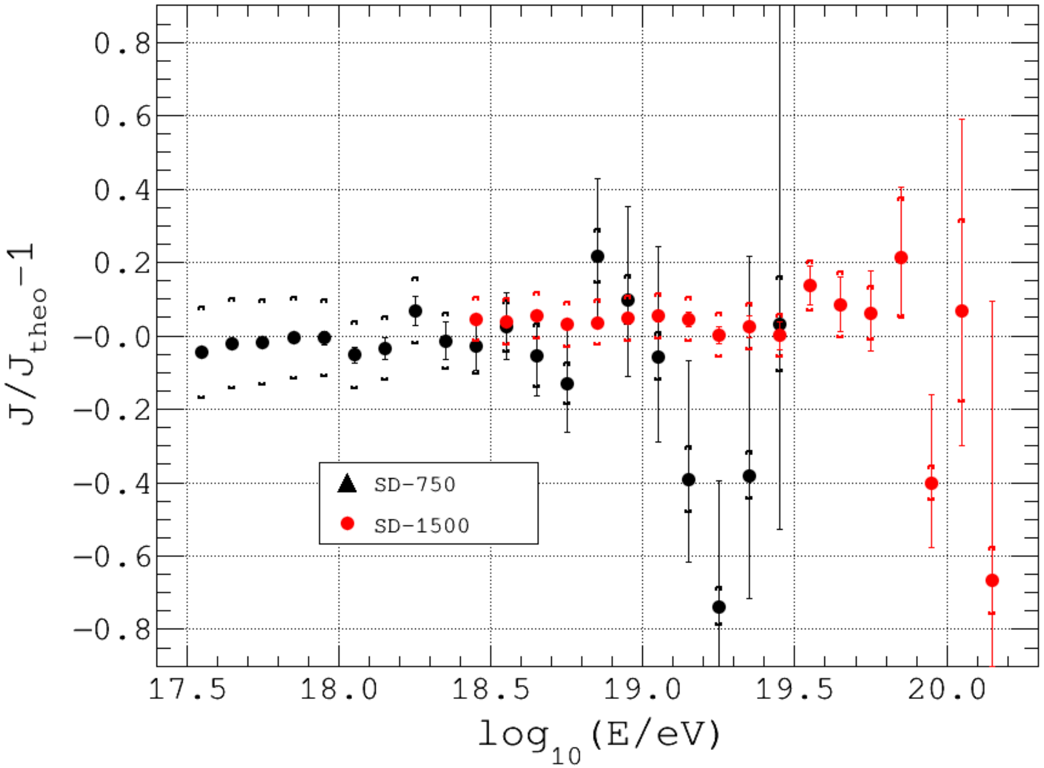

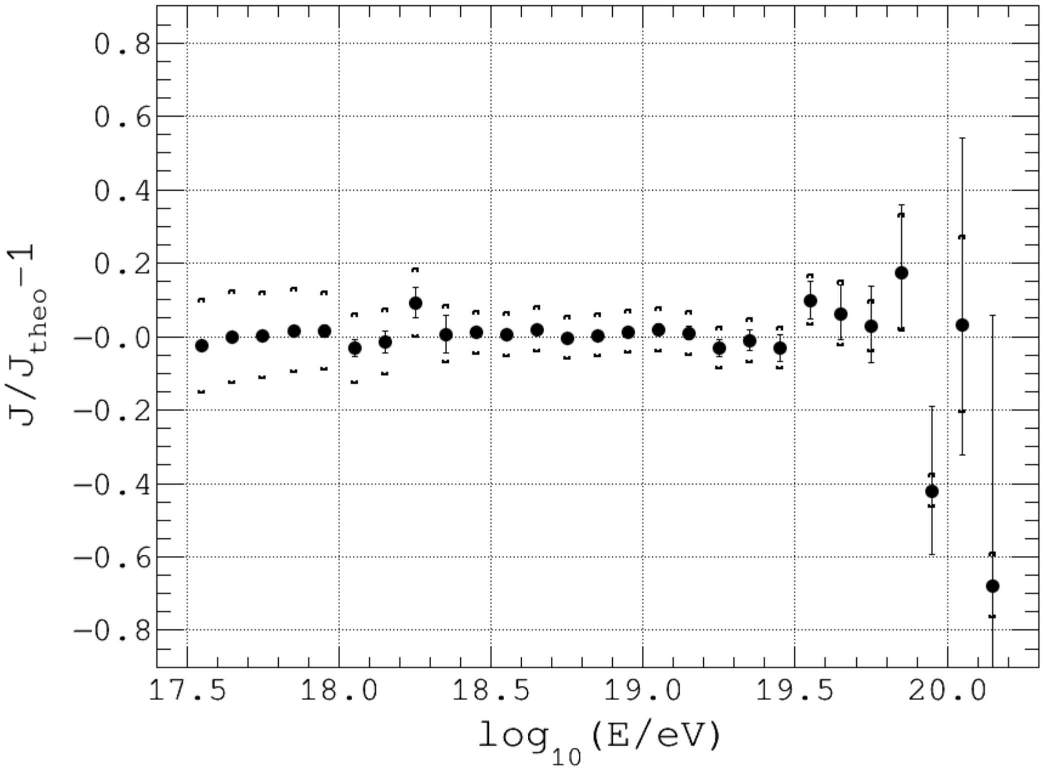

Infille spectrum fit : residual plot

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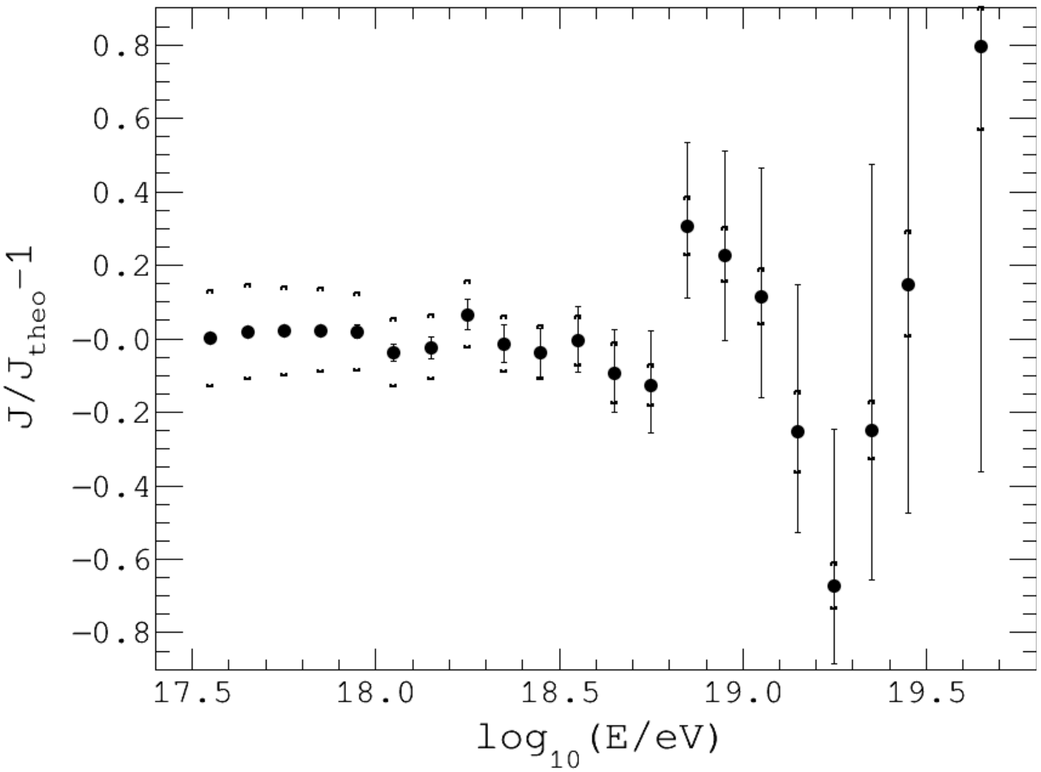

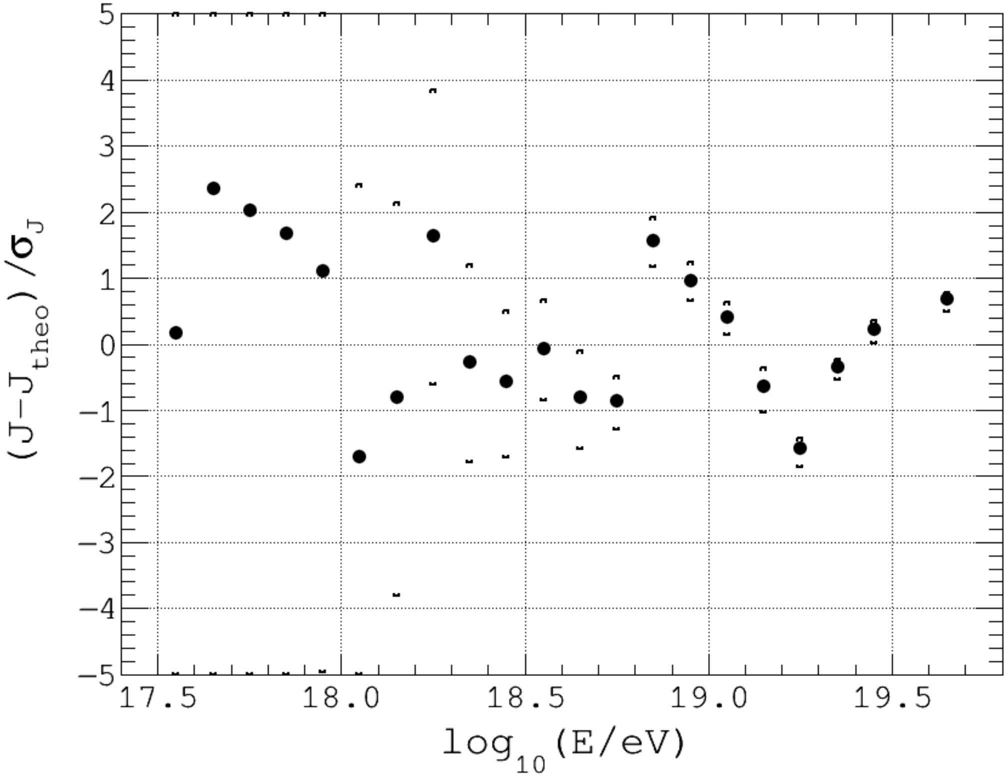

Combined spectrum: comparison with previous analyses

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	This work	ICRC-2015	[A. Schulz. for the Pierre Auger Collaboration, Internal note 2016]
Combination	SD-750 + SD-1500	All the four spectra	SD-750 + SD-1500
$\log_{10}(E_a/eV)$	18.68 ± 0.01	18.683 ± 0.006	18.72 ± 0.01
γ_1	- 3.33 ± 0.02	- 3.29 ± 0.02	- 3.20 ± 0.01
γ_2	- 2.53 ± 0.04	- 2.60 ± 0.02	- 2.52 ± 0.03
$\log_{10}(E_s/eV)$	19.57 ± 0.03	19.624 ± 0.017	19.56 ± 0.03
$\Delta\gamma$	2.6 ± 0.2	3.14 ± 0.2	2.6 ± 0.2