Energy spectrum of cosmic rays measured at the Pierre Auger Observatory and its low-energy extension

PIERRE AUGER OBSERVATORY

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Motivation and outline

- all-particle energy spectrum of CR between 10^{15}-10^{20} eV

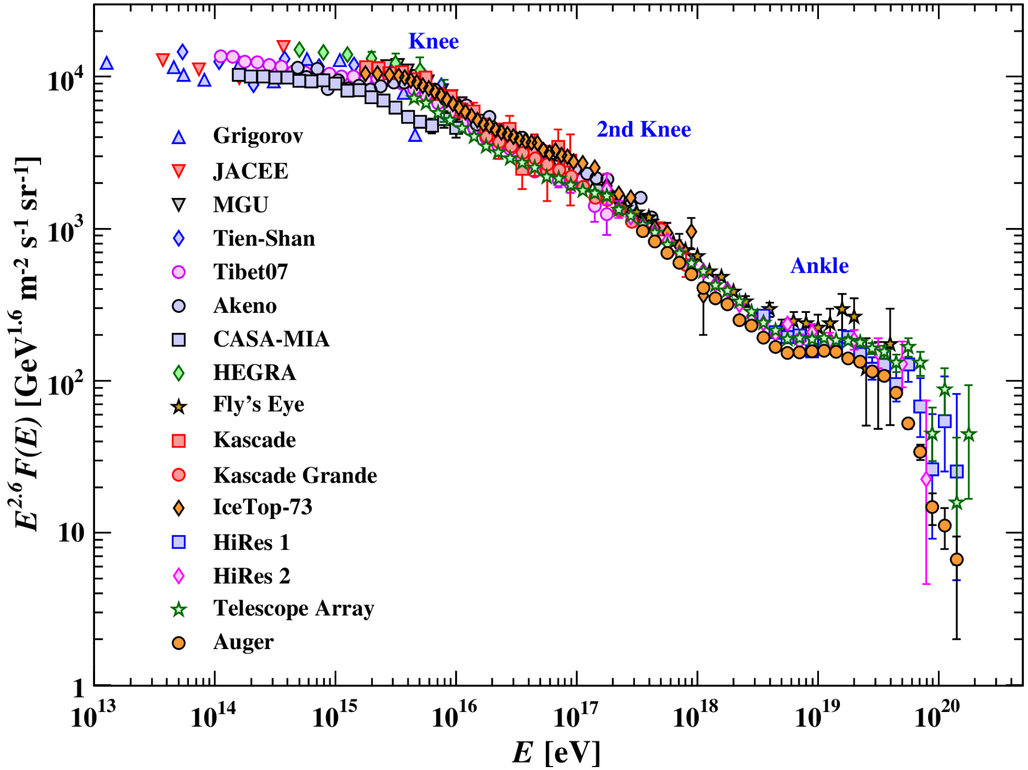
- transition from Galactic to extragalactic origin of CR particles
- changes in the mass composition of primaries

- now the **Pierre Auger Observatory** provides measurement using **the same energy scale**

1) Detection methods used at the Pierre Auger Observatory

2) Low-energy extension of the spectrum – summary of PhD thesis*

3) Recent results at the highest energies – published 16 Semptember 2020 in PRL, PRD+



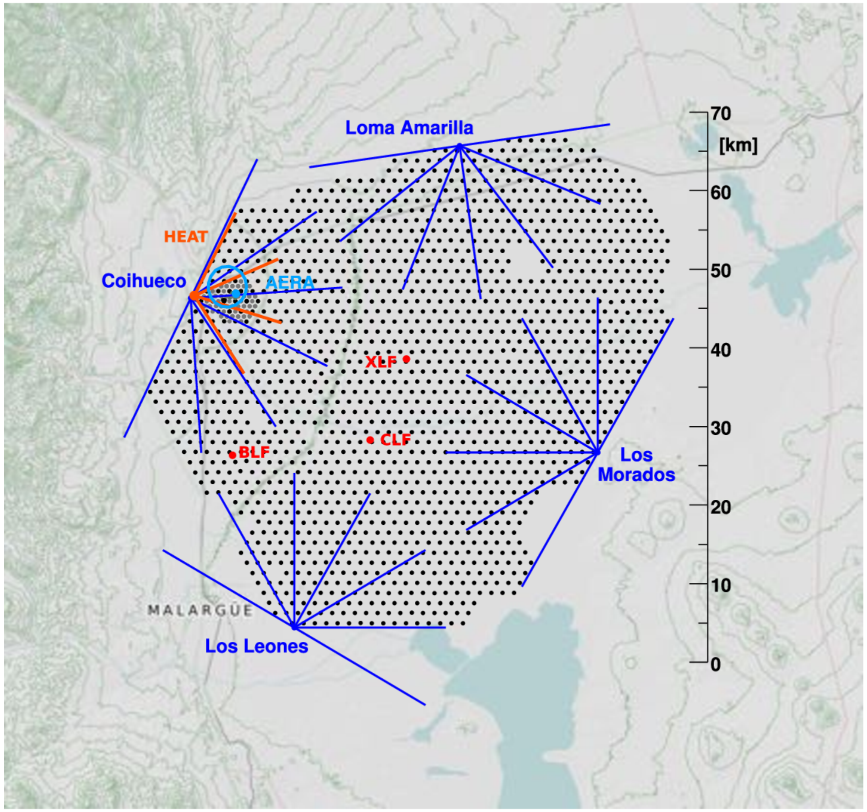
* Novotný V., Measurement of the energy spectrum of cosmic rays using Cherenkov-dominated data at the Pierre Auger Observatory, MFF UK, 2020

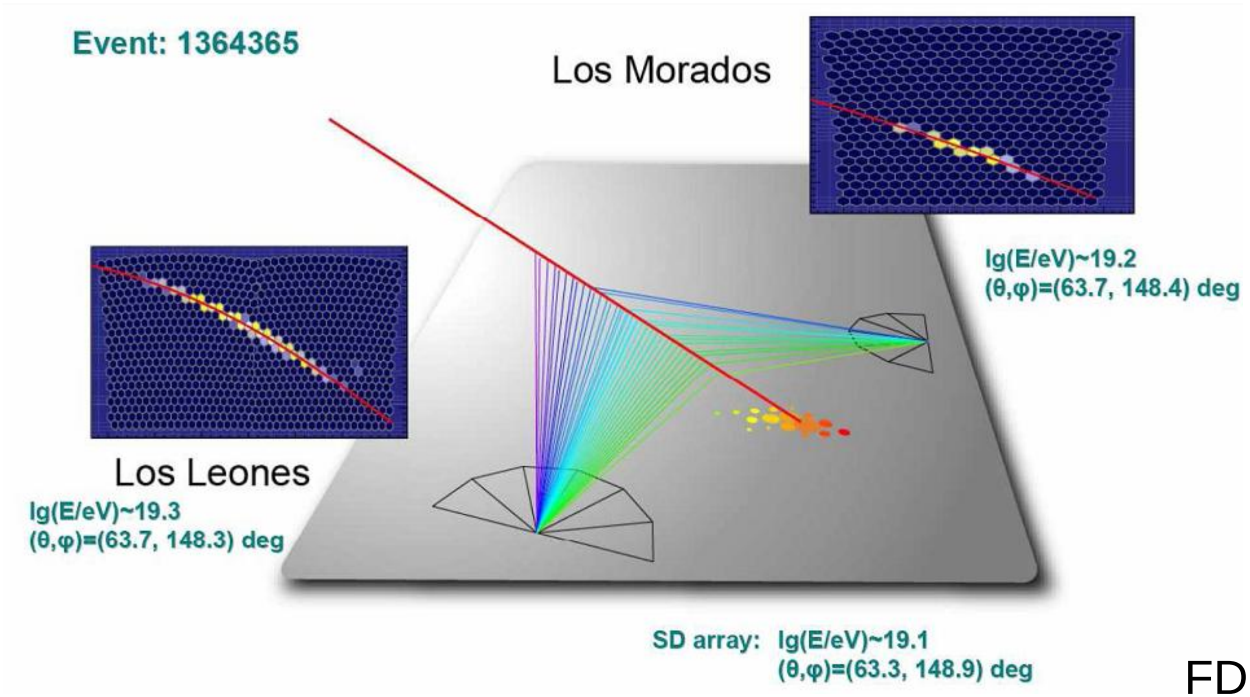
+ The Pierre Auger Collaboration, Features of the energy spectrum of cosmic rays above 2.5×10^{18} eV using the Pierre Auger Observatory, Physical Review Letters 125, 121106 (2020) (Editor's Suggestion)

+ The Pierre Auger Collaboration, A measurement of the cosmic ray energy spectrum above 2.5×10^{18} eV using the Pierre Auger Observatory, Physical Review D 102, 062005 (2020) (Editor's Suggestion)

Pierre Auger Observatory

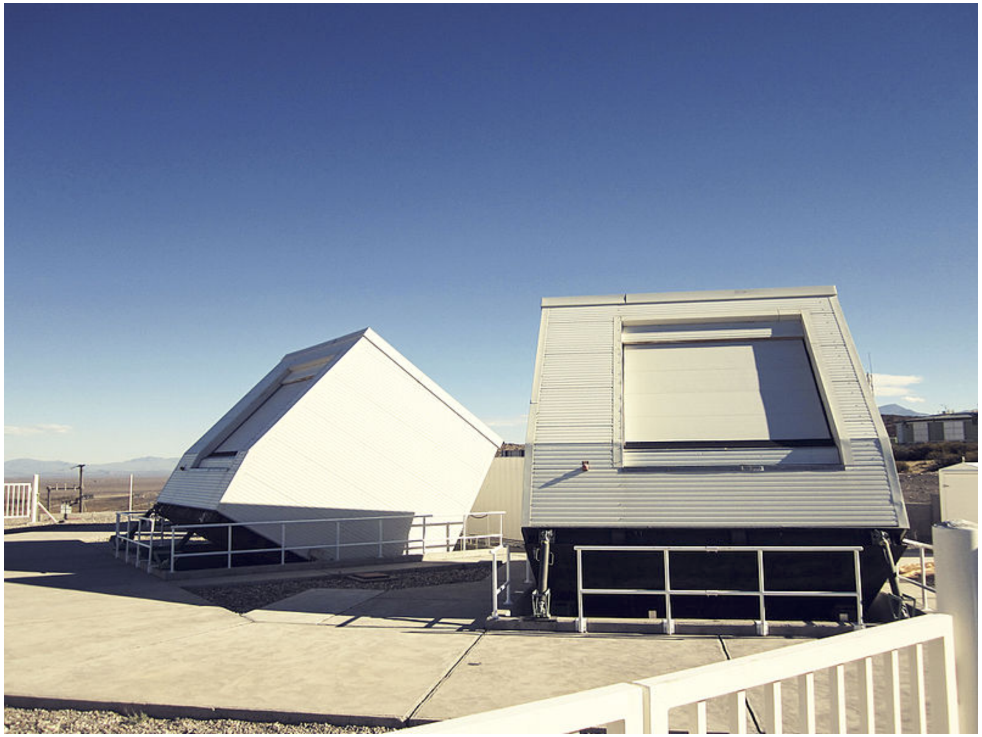
- **Surface detector** (SD) - water-Cherenkov stations
    - main array – 1500 m spacing
    - Infill array – 750 m spacing, low energy extension
- **Fluorescence detector** (FD)
    - 24 telescopes at 4 sites – overlook SD horizontaly (FOV 0°-30° in elevation)
    - 3 **High Elevation Auger Telescopes** (HEAT) – near Infill (30°-60°), low energy extension
- **hybrid** measurement = FD+SD





FD – Los Leones

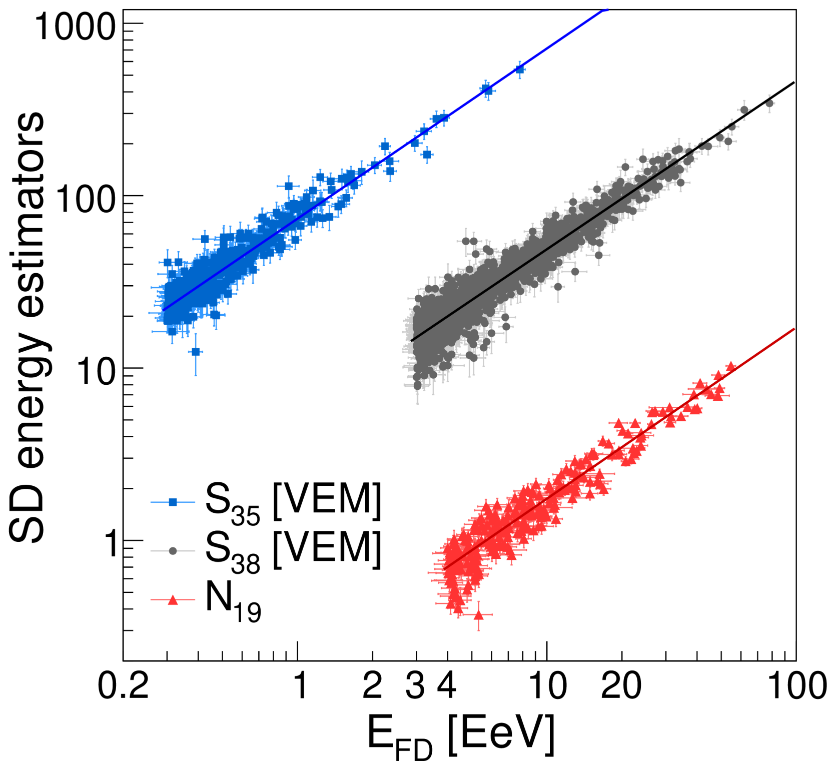
HEAT



Energy spectrum measurements

- **Surface detector** – ontime ~100% → **larger statistics**
- **Fluorescence detector** – calorimetric energy → **lower systematic uncertainty**
- SD is calibrated to energies measured in FD – **the same energy scale**
    - subset of events reconstructed in both FD and SD simultaneously

- 3 different SD measurements
    - **SD 1500 vertical*** – main array – S_{38}
    - **SD 750 vertical** – Infill array – S_{35}
    - **SD 1500 horizontal** – main array – N_{19}



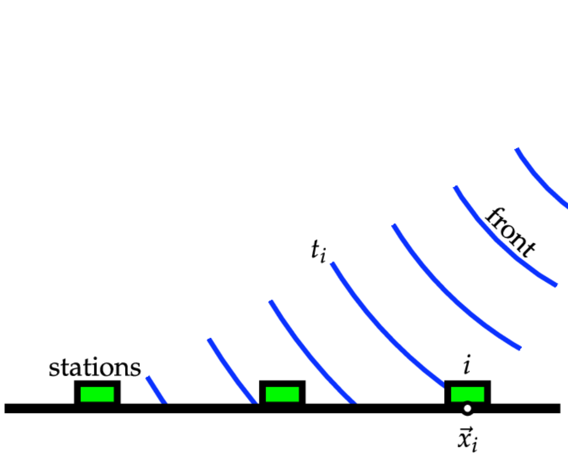
- FD in hybrid reconstruction mode
    - time from SD used in the axis geometry fit
    - calibration and the **hybrid spectrum**

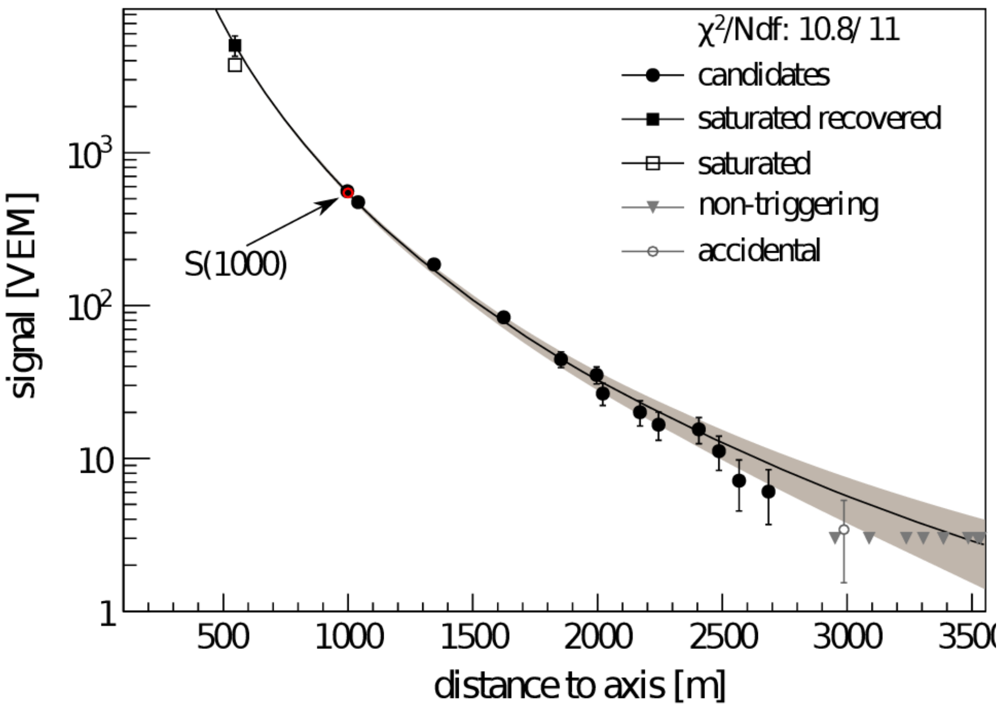
- FD in Cherenkov mode
    - developed in the PhD thesis
    - **Cherenkov spectrum** (from Cherenkov-dominated events)

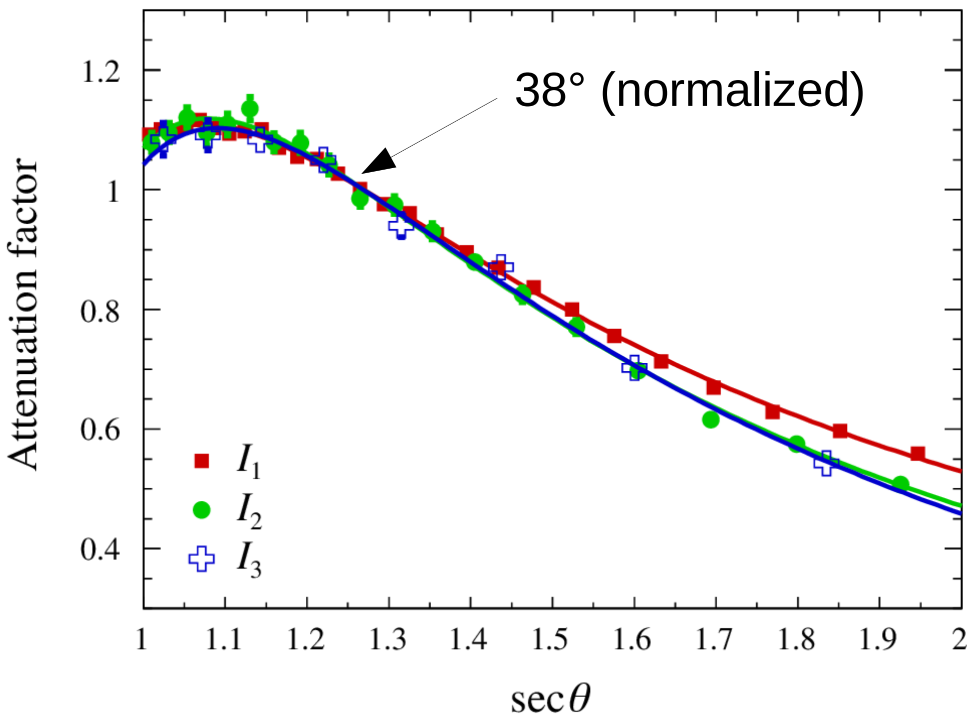
- *** new results discussed below**

Reconstruction - surface detector
vertical events

- zenith angles 0°-60°
- dominated by EM component
- shower axis rec. from trigger times of statins
- shower size estimator S(1000) (LDF fit)
  - → energy estimator S_{38} (CIC method)
- Infill – S(1000) → S(450), S_{38} → S_{35}, zenith < 40°



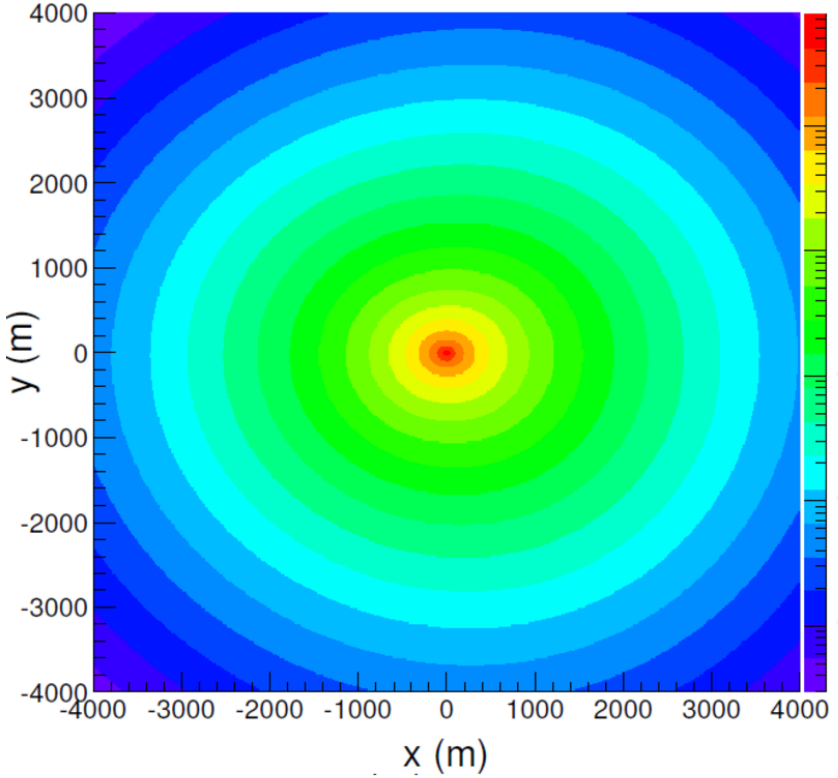




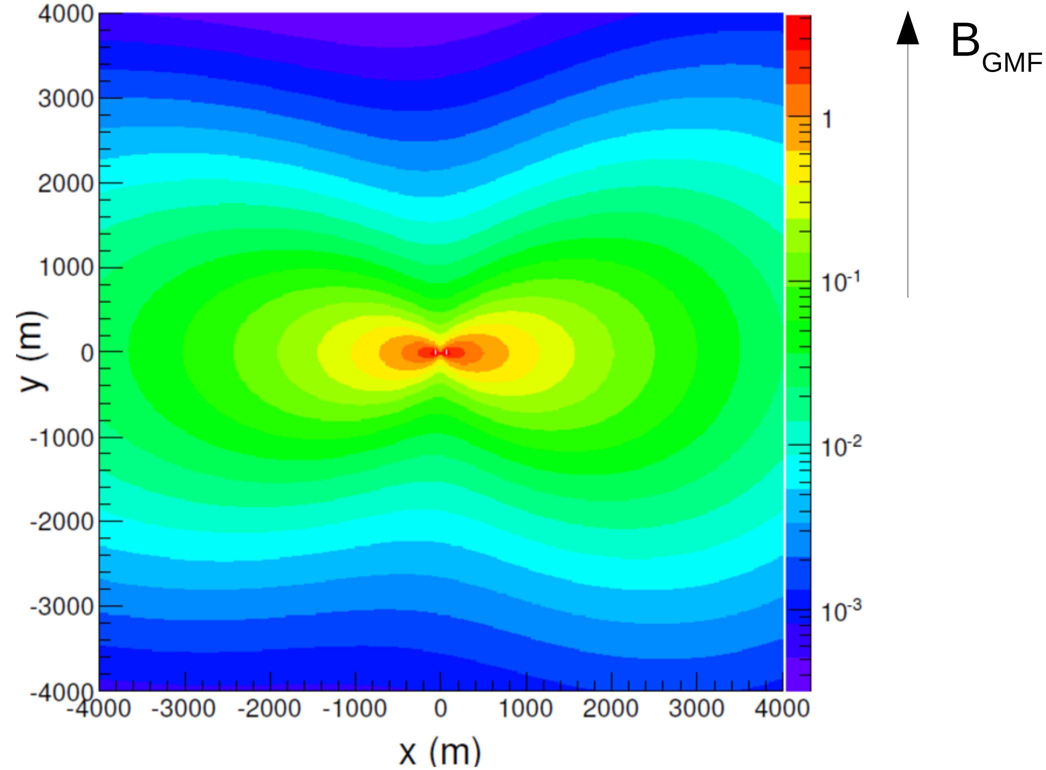
Reconstruction - surface detector
horizontal events

- zenith > 60°
- signal dominated by muons – deflected by geomagnetic field
- shower reconstruction uses simulated muon density maps (p@10^{19} eV) - $\rho_s(\vec{r},\theta,\phi)$
- N_{19} is the normalization factor in $\rho_m(\vec{r}) = N_{19}\rho_s(\vec{r},\theta,\phi)$

zenith = 70°



zenith = 84°



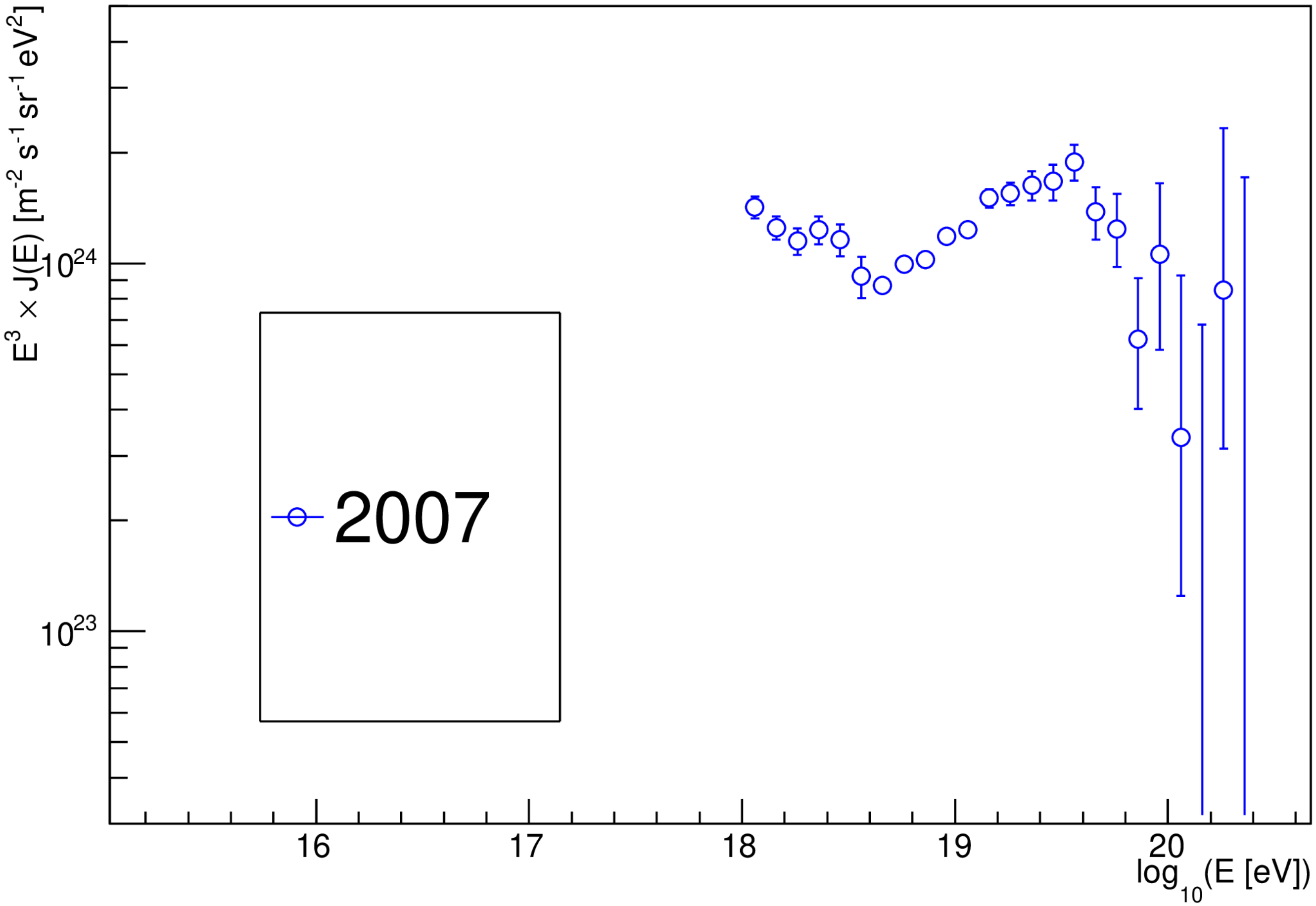
shower plane = perpendicular to shower axis

Auger energy spectrum

- combined spectrum – evolution in time

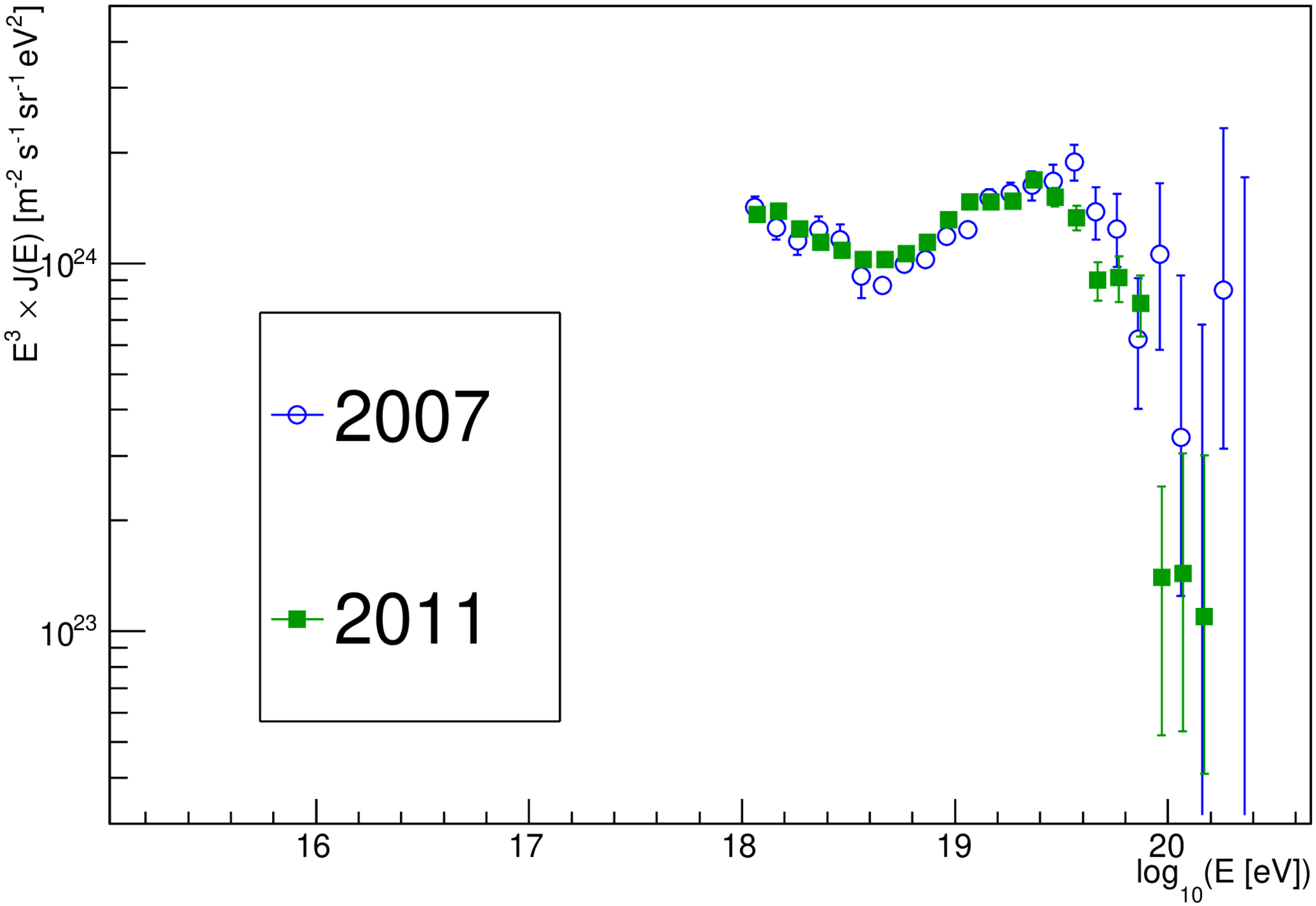
Auger energy spectrum

- combined spectrum – evolution in time
- 2007 - the first result from the Pierre Auger Observatory data (array not finished)



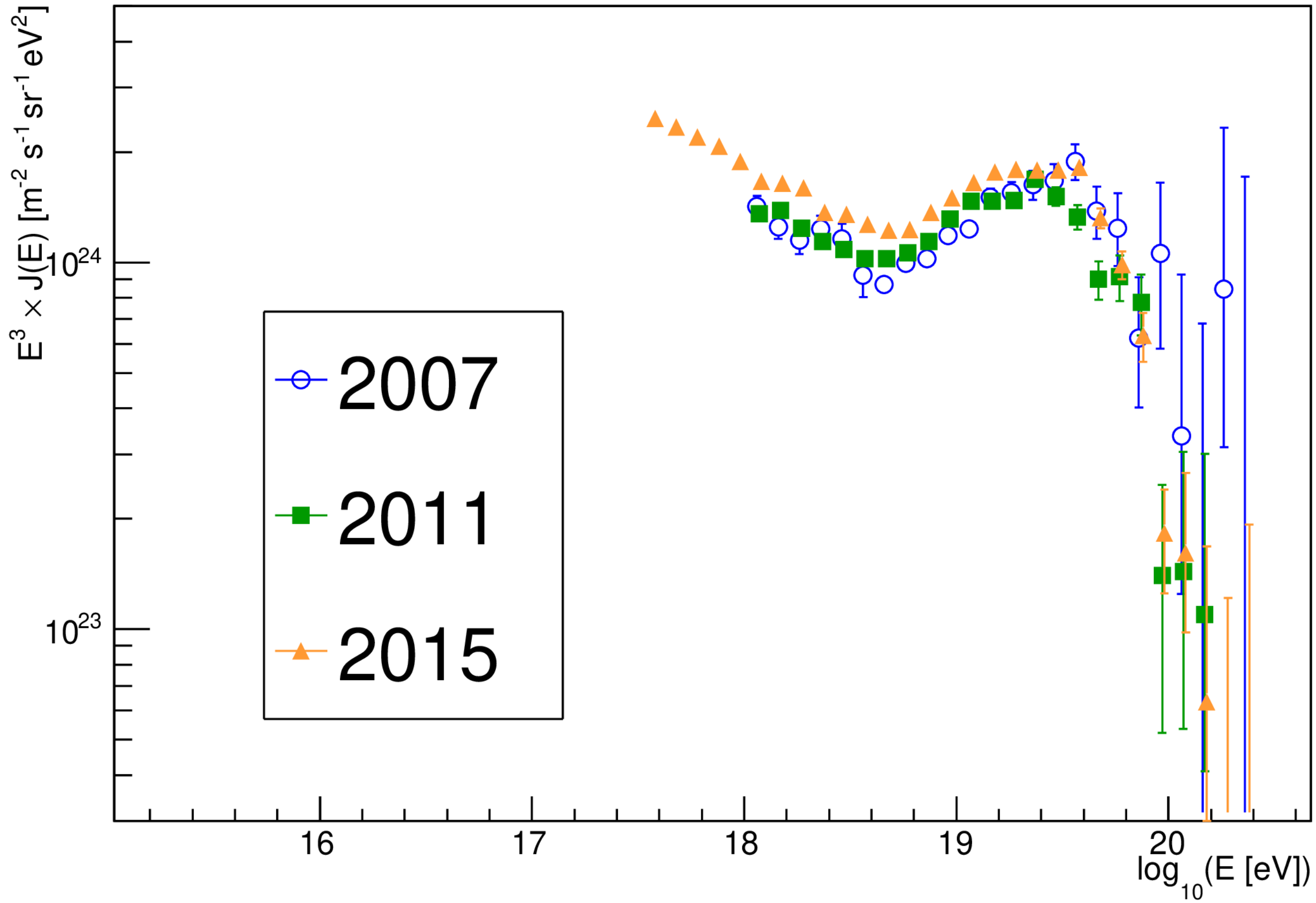
Auger energy spectrum

- combined spectrum – evolution in time
- 2011 – decrease of the CR flux well measured above $5x10^{19}$ eV



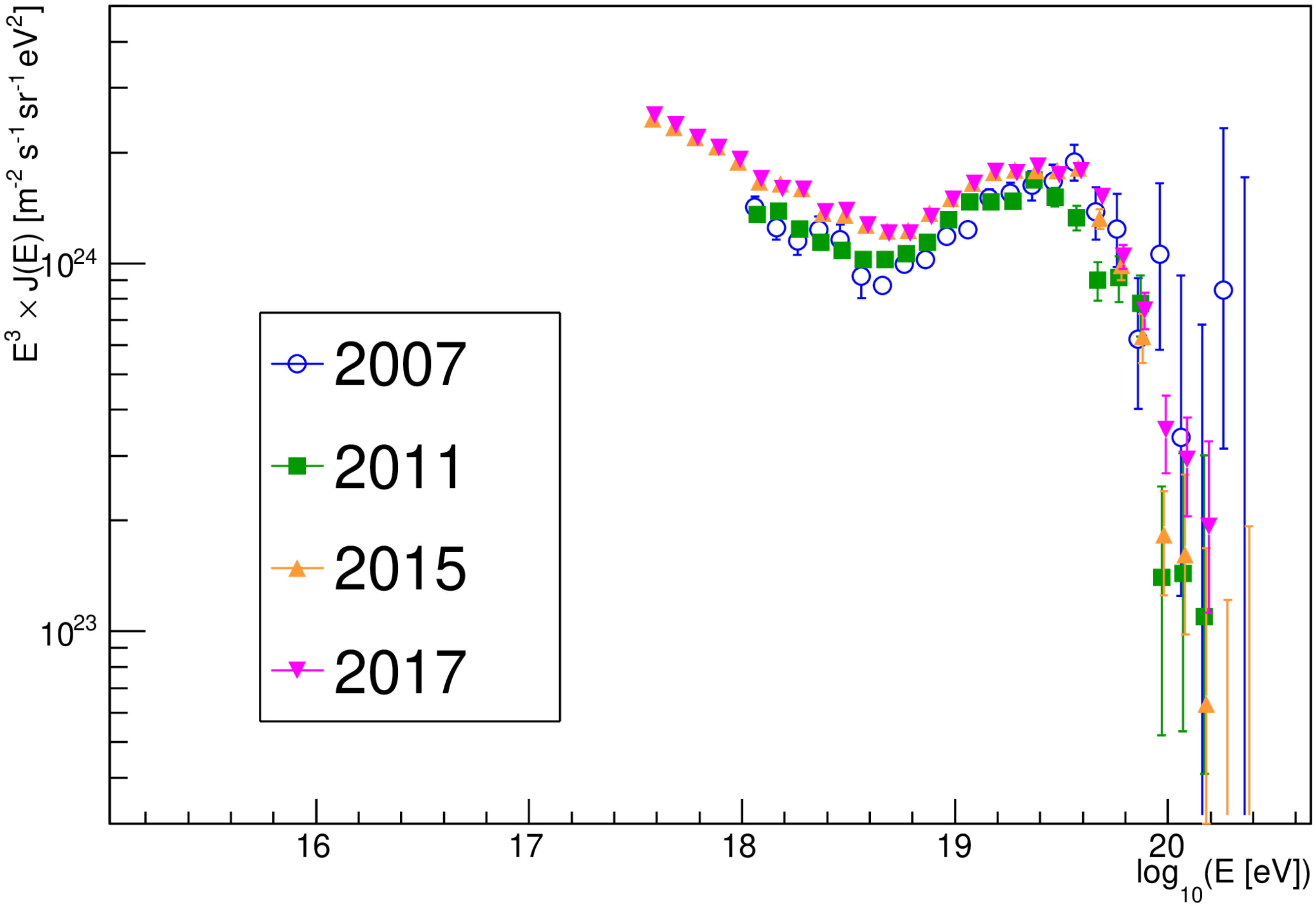
Auger energy spectrum

- combined spectrum – evolution in time
- 2015 – energy scale updated + first results from the Infill array



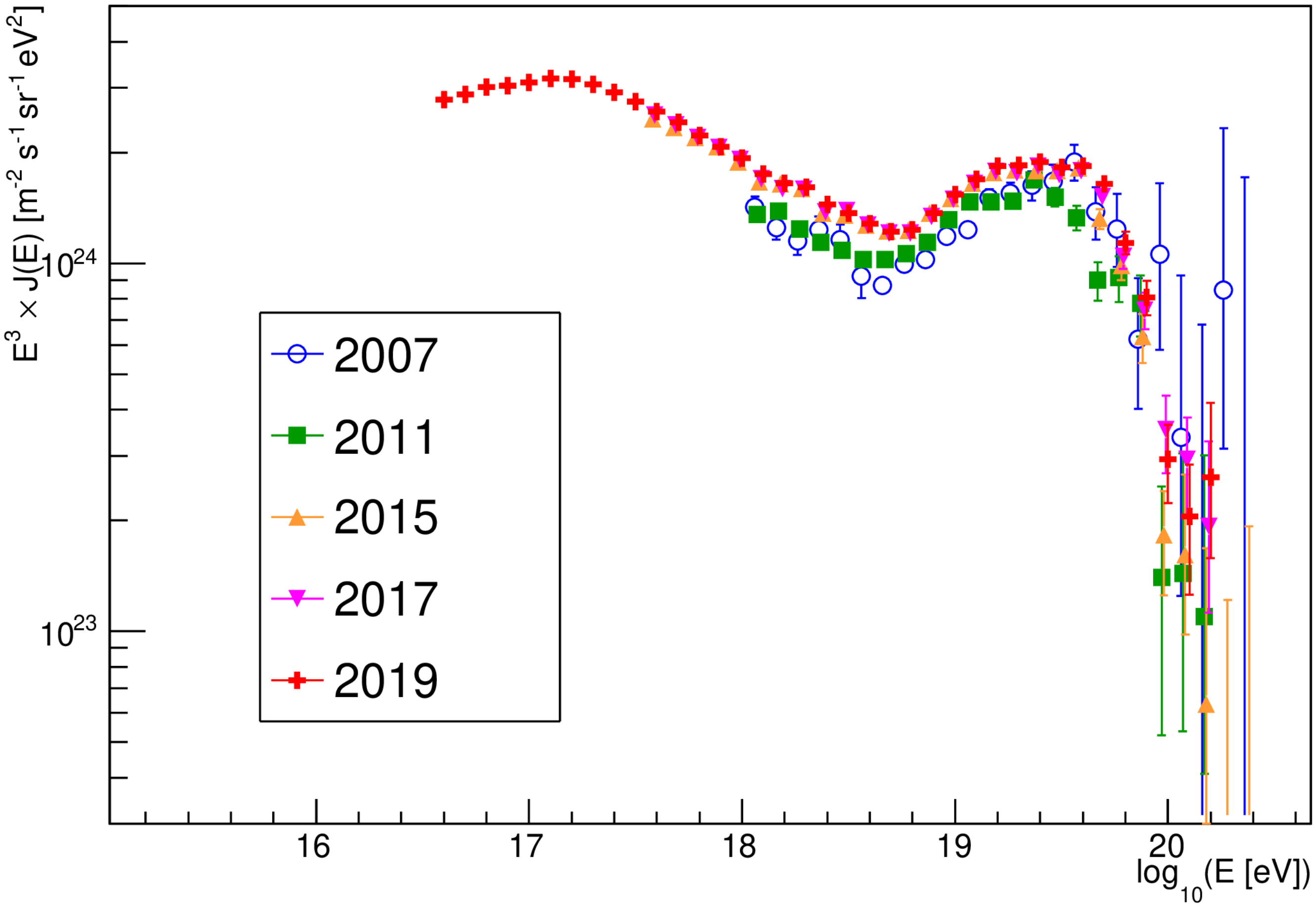
Auger energy spectrum

- combined spectrum – evolution in time
- 2017 – decrease of the flux above $5x10^{19}$ eV measured in hybrid data



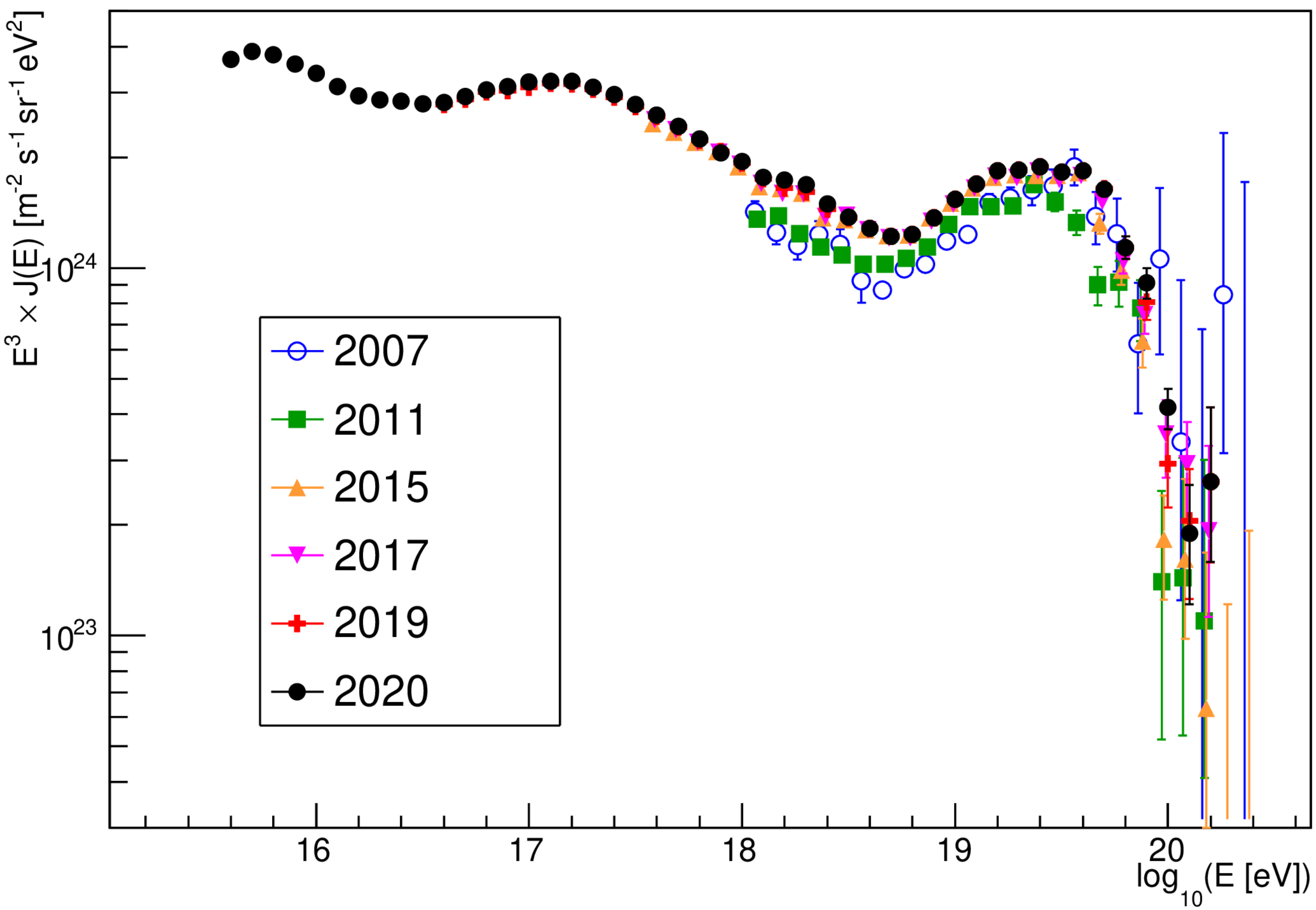
Auger energy spectrum

- combined spectrum – evolution in time
- 2019 - **2^{nd} knee measured - result of the Cherenkov analysis**



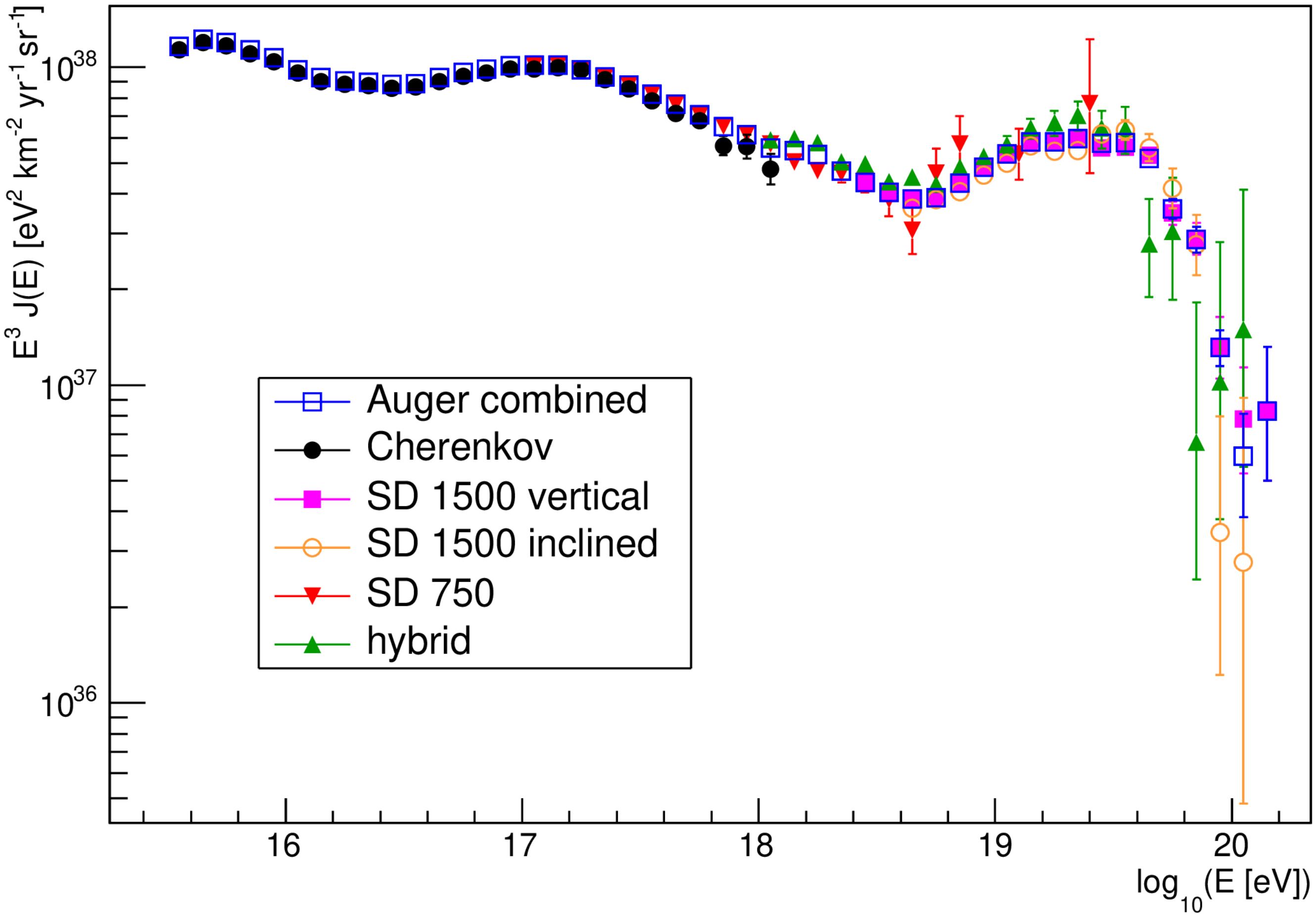
Auger energy spectrum

- combined spectrum – evolution in time
- 2019 - **2^{nd} knee measured - result of the Cherenkov analysis**
- 2020 **– further decrease of the energy threshold** – result of the PhD thesis



Auger energy spectrum

- 2020 – combination of 5 different methods
- **Cherenkov spectrum – low energy extension in the range $10^{15.5}$ – $10^{18.1}$ eV**



Differences between FD and SD analyses

Surface detector

+ - **larger statistics**
  - exposure calculated geometrically
- - worse energy resolution
+ - ~100% trigger efficiency above threshold
- - biases due to uncertain CR composition below threshold

Fluorescence detector

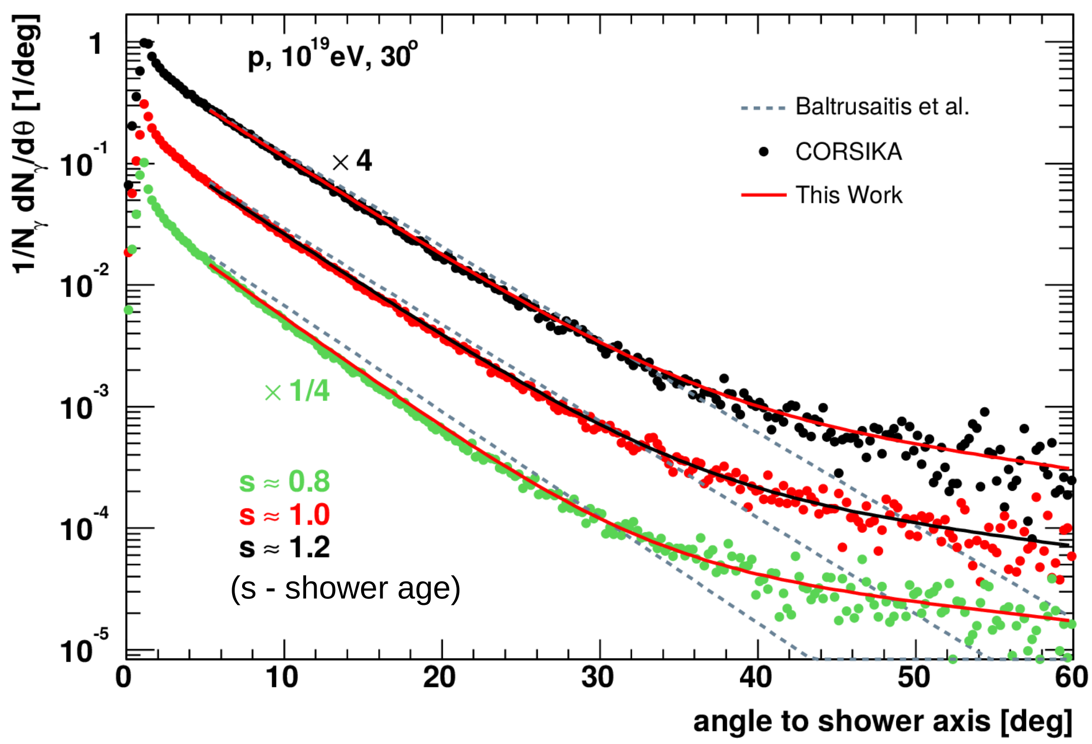
- - lower statistics (ontime ~13% wrt. SD)
  - exposure calculated from Monte Carlo simulations
+ - **better energy resolution**
+ - biases due to uncertain CR composition under control – lower energies accessible

Fluorescence detector in Cherenkov regime

+ - **lower detection threshold**
- - exposure limited to showers pointing towards FD telescopes
  - shower reconstruction without SD

Cherenkov radiation from EAS

- **collimated** around shower axis
- produced by charged particles – dominated by **electrons+positrons**
  - recalculation to energy deposit from MC
  - amount of light calculated analytically – lower systematic uncertainty
- particles in shower are scattered – emission also outside of the inner Cherenkov cone



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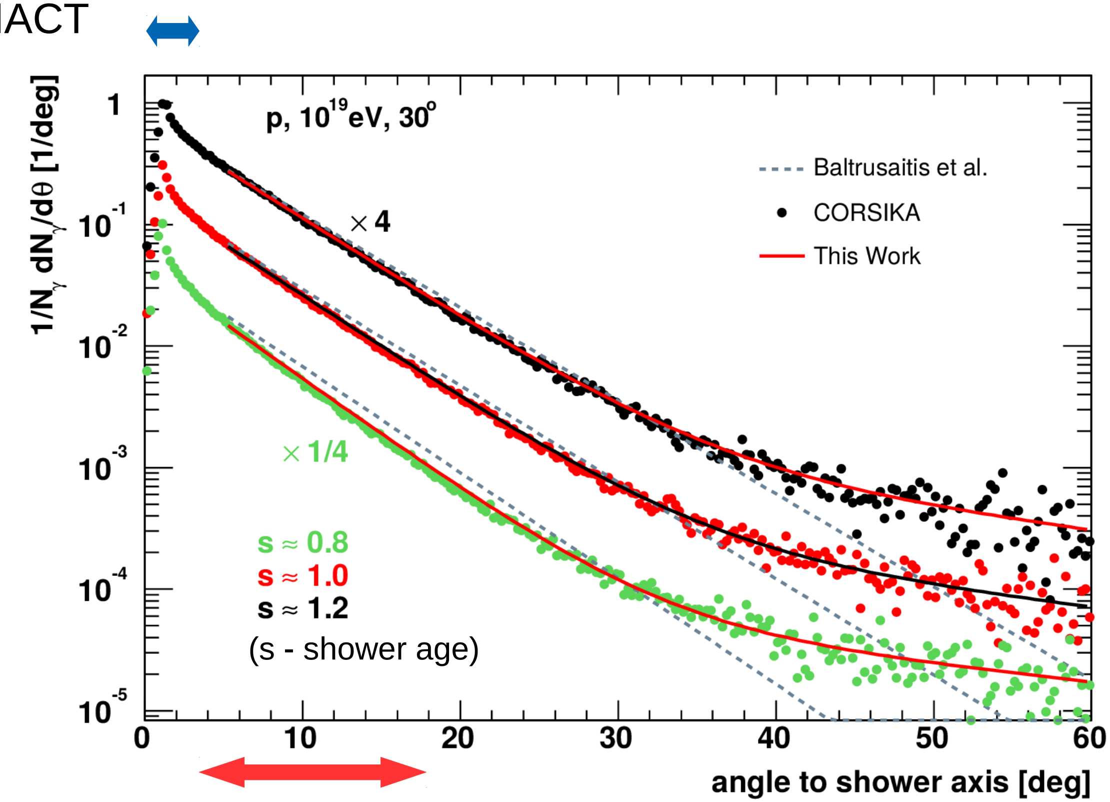
range of IACT

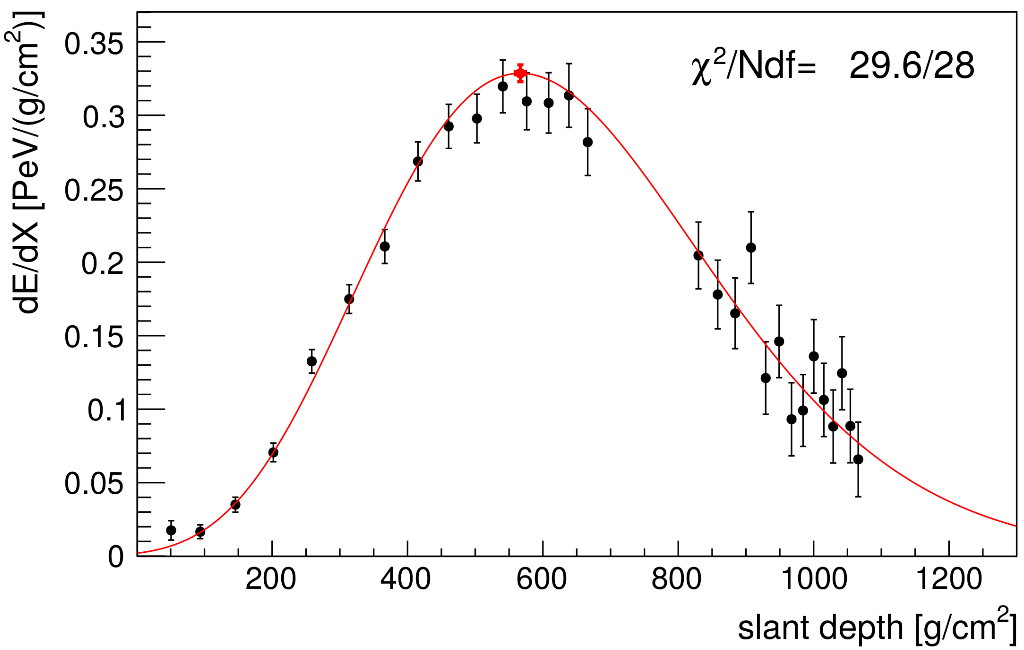


typical range of viewing angles of the Cherenkov-dominated events at Auger

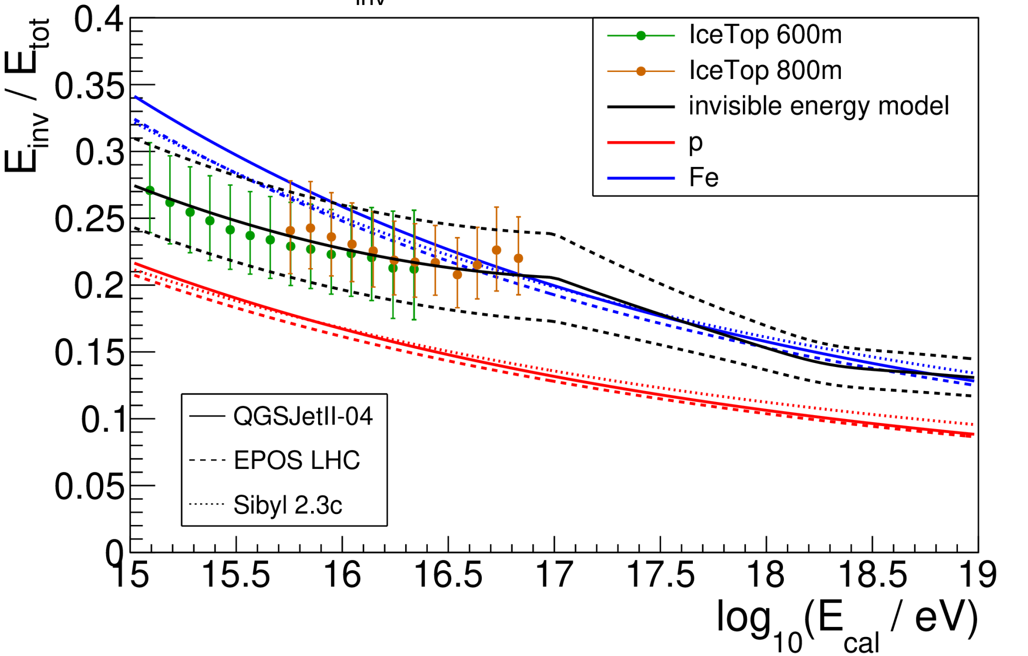
Cherenkov-dominated events

- **calorimetric energy** (E_{cal}) – integral of the longitudinal profile
- information about shower is **compressed in time** – consequence of the shower geometry
    - detector effects are important
- total energy – **correction for the invisible energy** (E_{inv})
    - its fraction increases with decreasing energy
    - **model of E_{inv}** used at Auger above 10^{17} eV prolongated down to 10^{15} eV in the thesis
        - IceTop data – measurement of the muon density on the ground

longitudinal profile

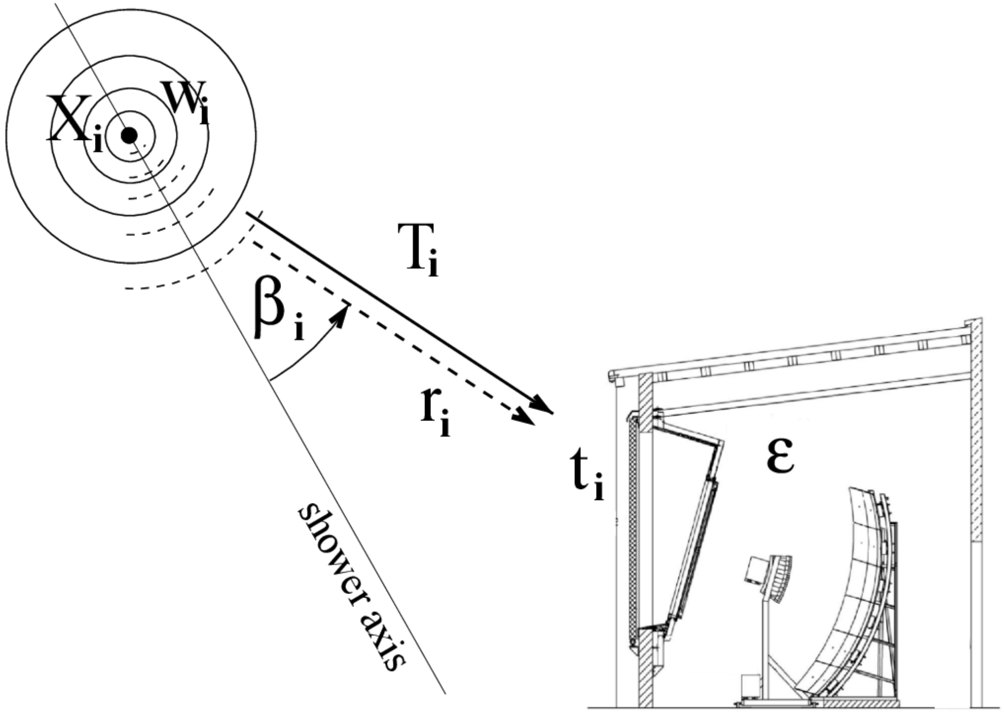


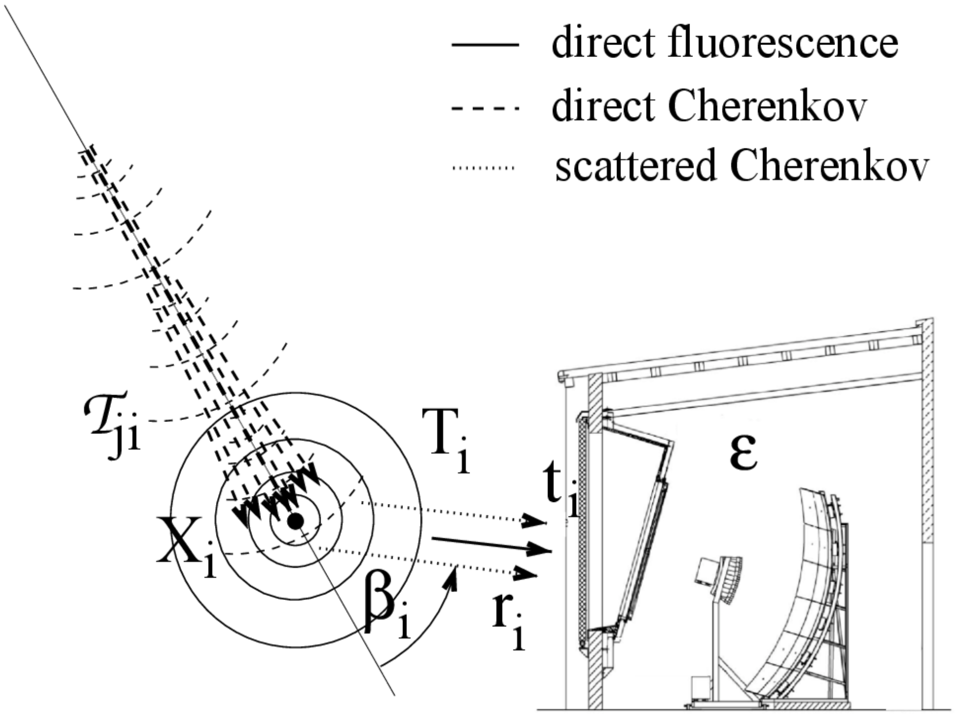
E_{inv} – invisible energy



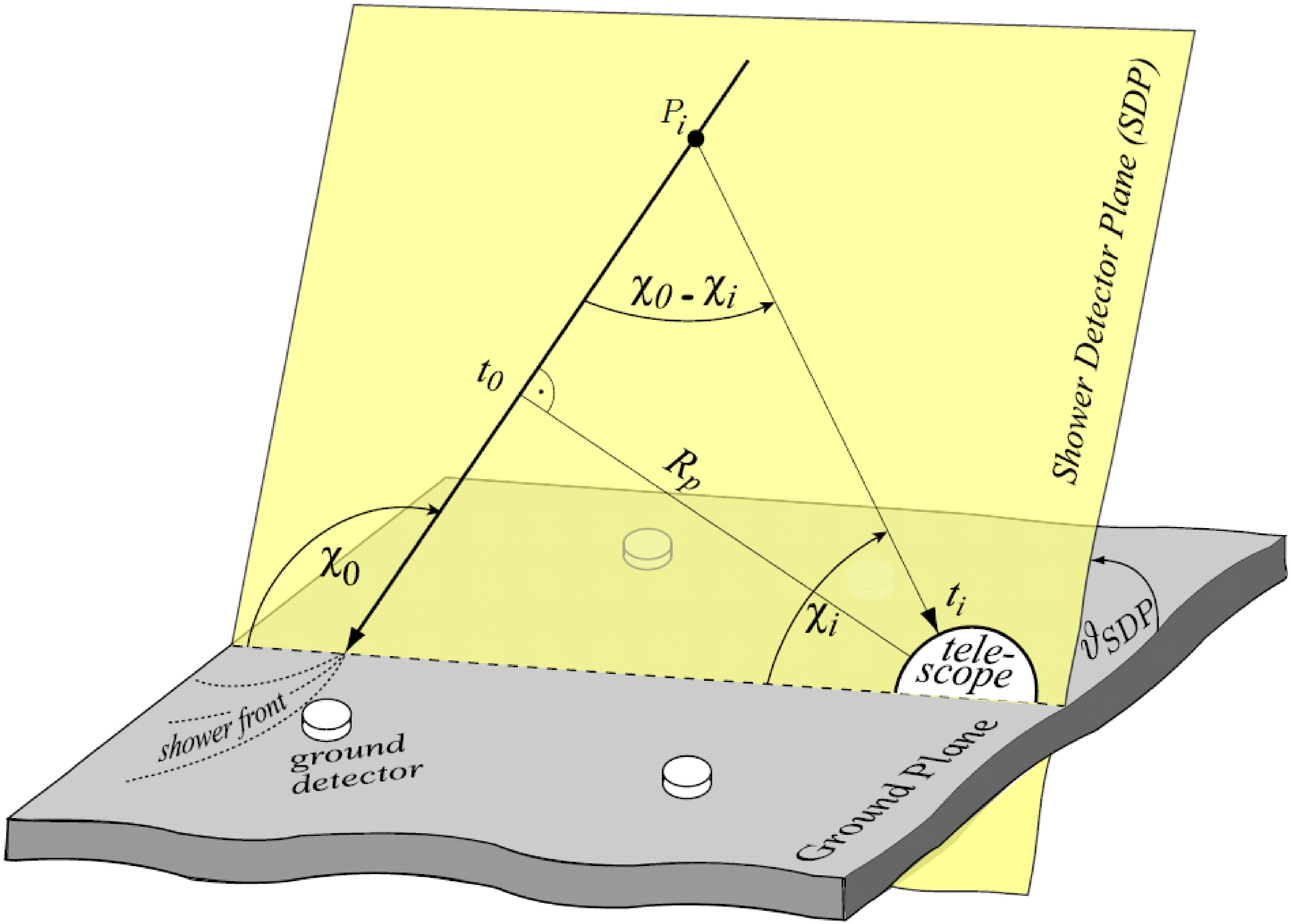
Reconstruction - fluorescence detector

- **shower axis geometry**
  - hybrid rec. - standard for fluorescence events
  - profile-constrained geometry fit (PCGF) - useful for Cherenkov-dominated events
  - SD rec. - better precision for distant showers
- **reconstruction of longitudinal profile**
  - Cherenkov-Fluorescence Matrix (CFM)
  - possible only for FD measurements





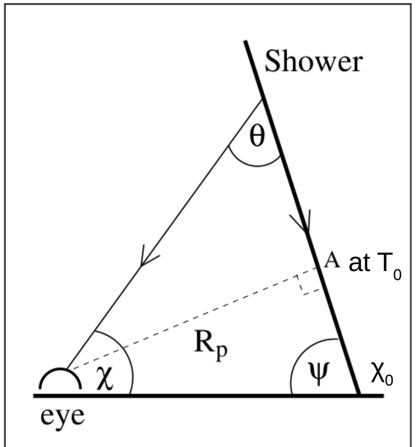
Definition of shower axis geometry



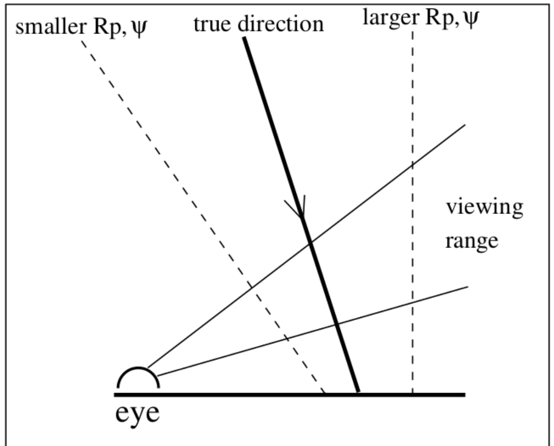
Profile-constrained geometry fit

Inside SDP

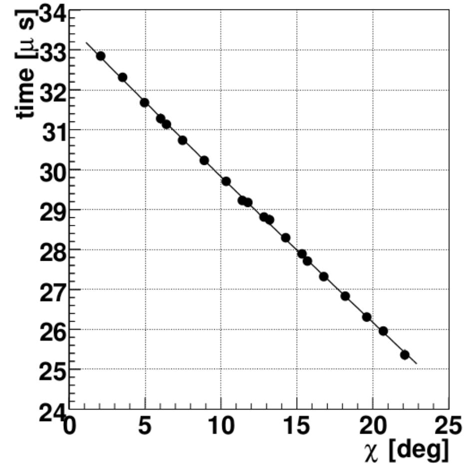
Problem in monocular reconstruction

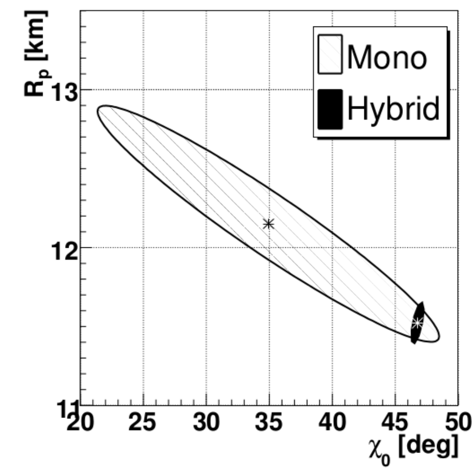


(a)



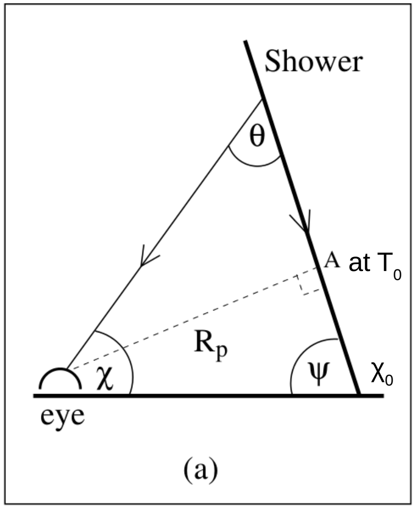
(b)

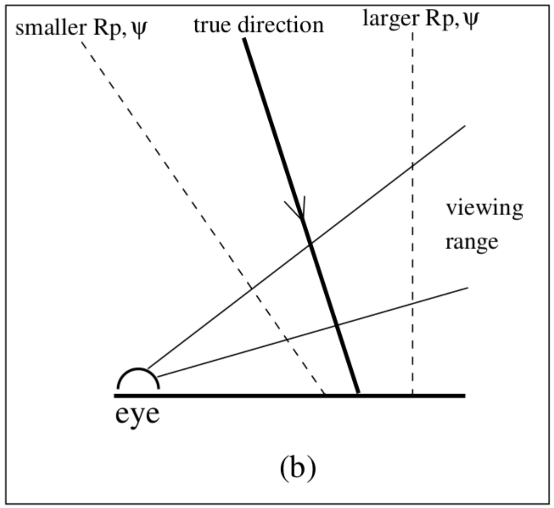




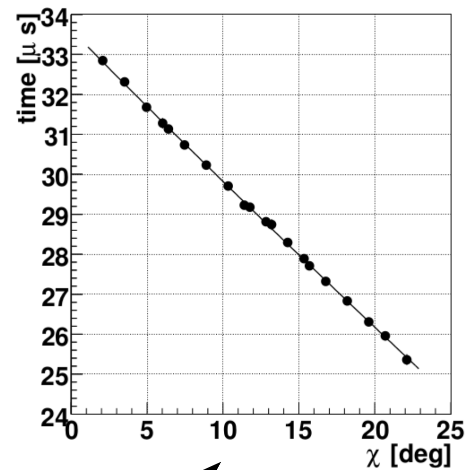
Profile-constrained geometry fit

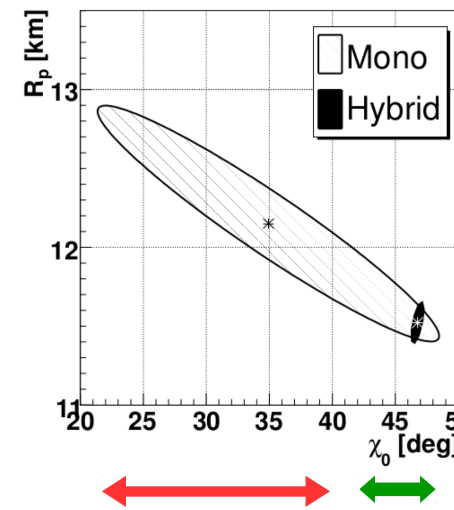
Inside SDP





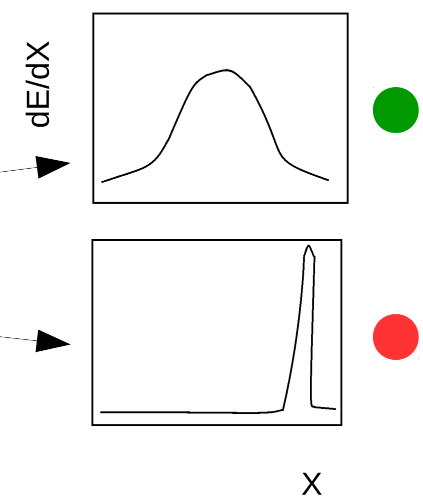
Problem in monocular reconstruction





- PCGF:

- scan in χ_0
  - R_p and T_0 from time fit → trial geometry
  - longitudinal profile from CFM
    - OK → possible geometry
    - not OK → wrong geometry
- the most likely geometry chosen

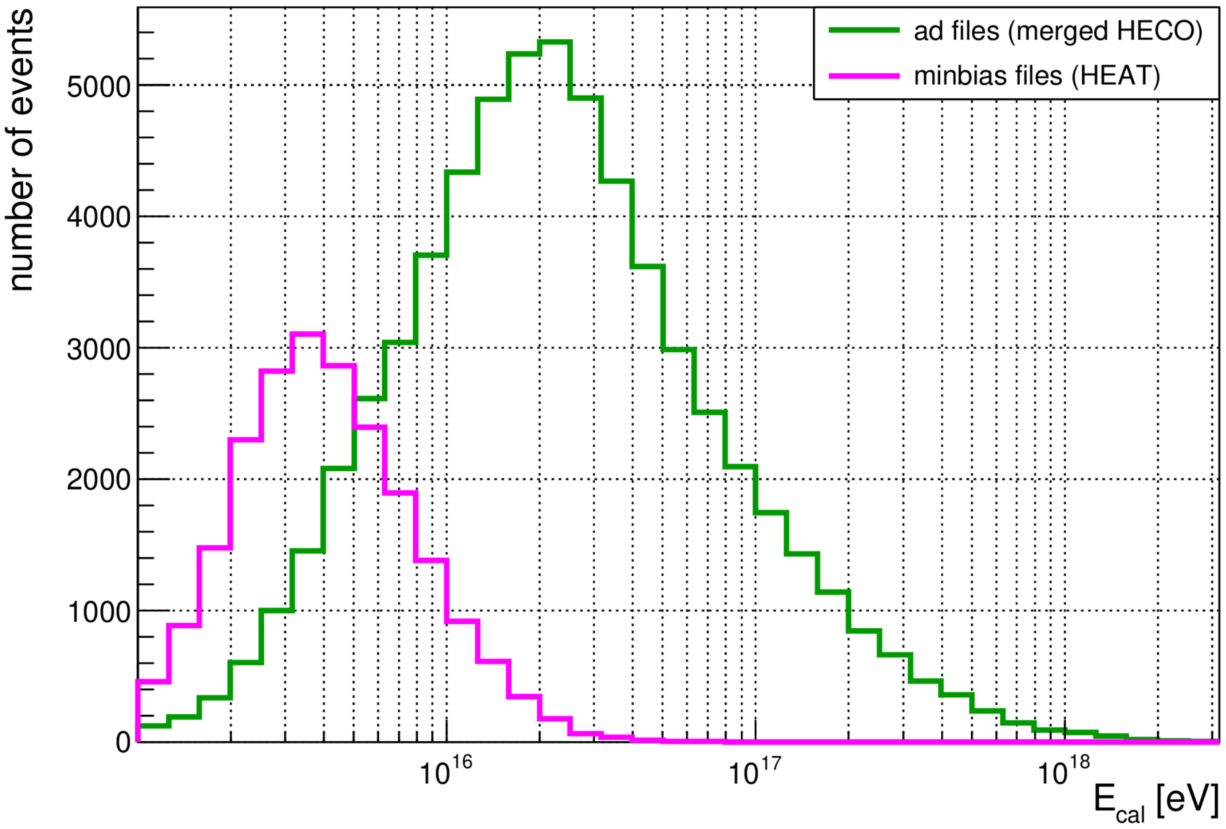


- the best performance for Cherenkov-dominated events

- detection of Cherenkov radiation is sensitive to shower geometry

Cherenkov-dominated data

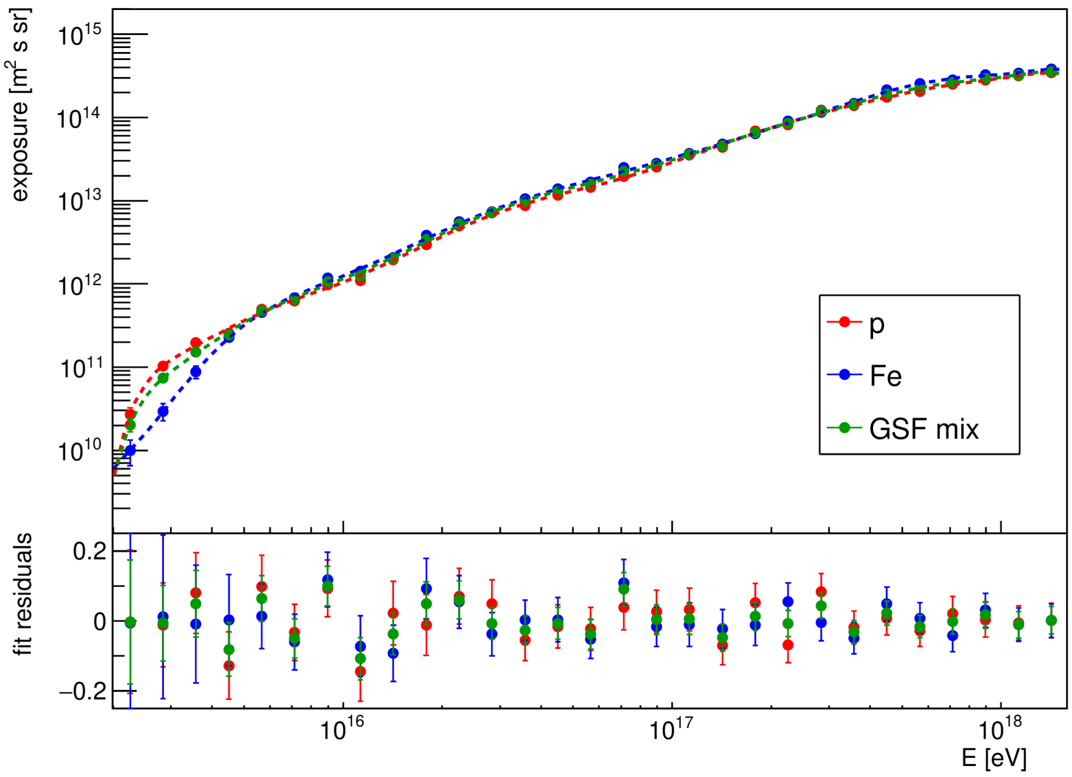
- **HEAT + Coihueco** telescopes
    - **fully triggered** – T3 trigger, merged HECO station
    - **minimum bias** data – TLT trigger, HEAT only, 10% of events stored
        - used in analysis for the first time
        - triggers intentionally developed to suppress Cherenkov-dominated events
- data after all detector, atmosphere and quality cuts



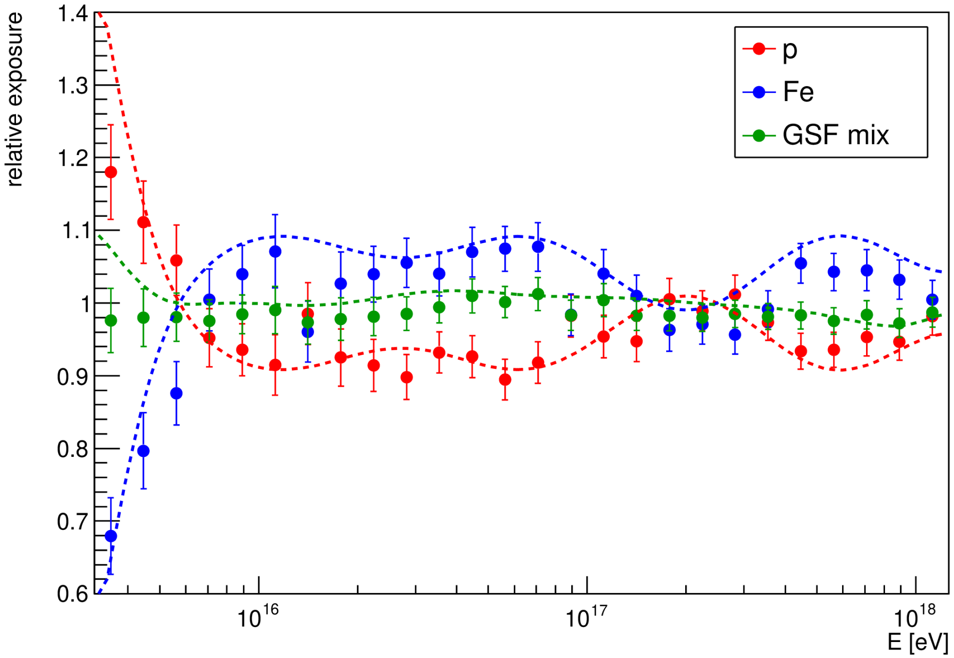
Exposure

- **detector sensitivity** to showers at given energy – integrated in time, area and solid angle
- calculated with the use of realistic **Monte Carlo simulations**
    - shower development
    - atmosphere properties
    - detector status
- depends on CR mass composition – differences below 10%
- energy spectrum – ratio of the data distribution and exposure

exposure



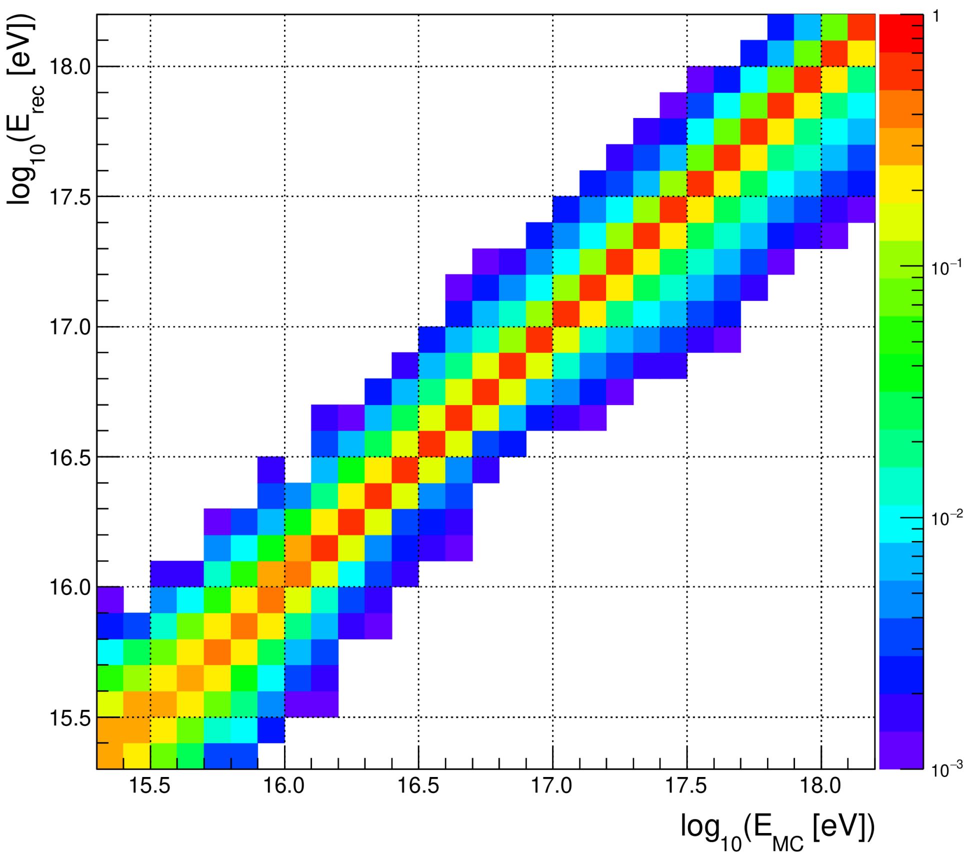
dependence on mass composition



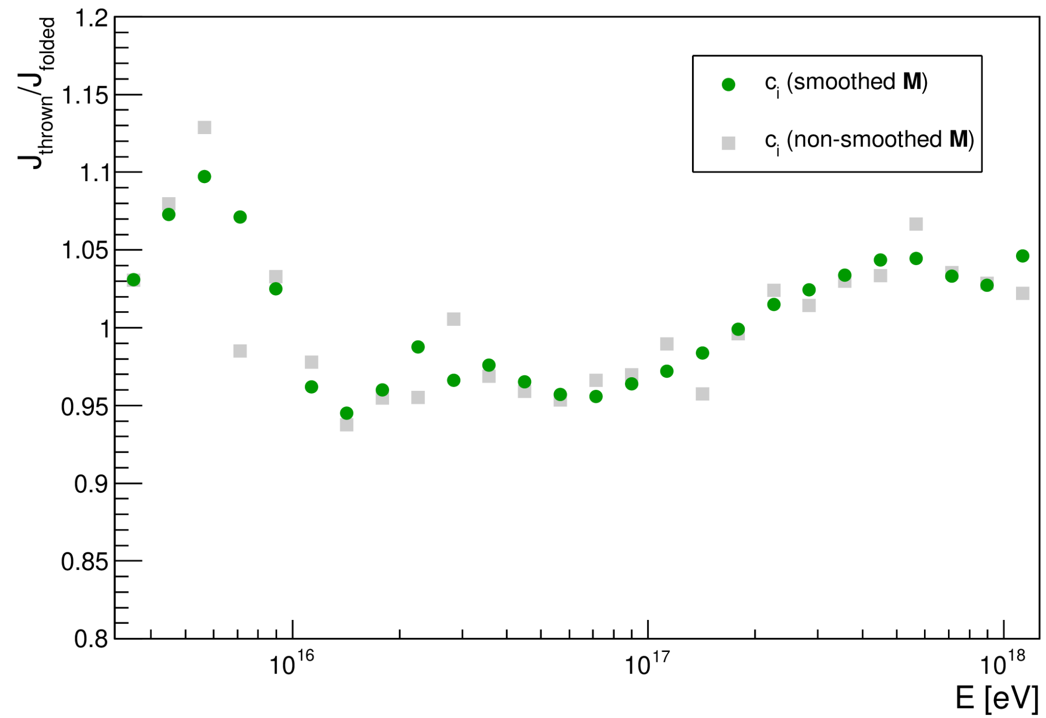
Correction for detector effects

- **finite detector resolution** – migration of reconstructed events between energy bins
    - dominated by the reconstruction resolution
- **forward folding** – correction used at Auger
    - fit of the parametrized spectrum to the data – functional form needed*
    - bin-by-bin correction factors – ratio of thrown and forward-folded spectrum

migration matrix



correction factors



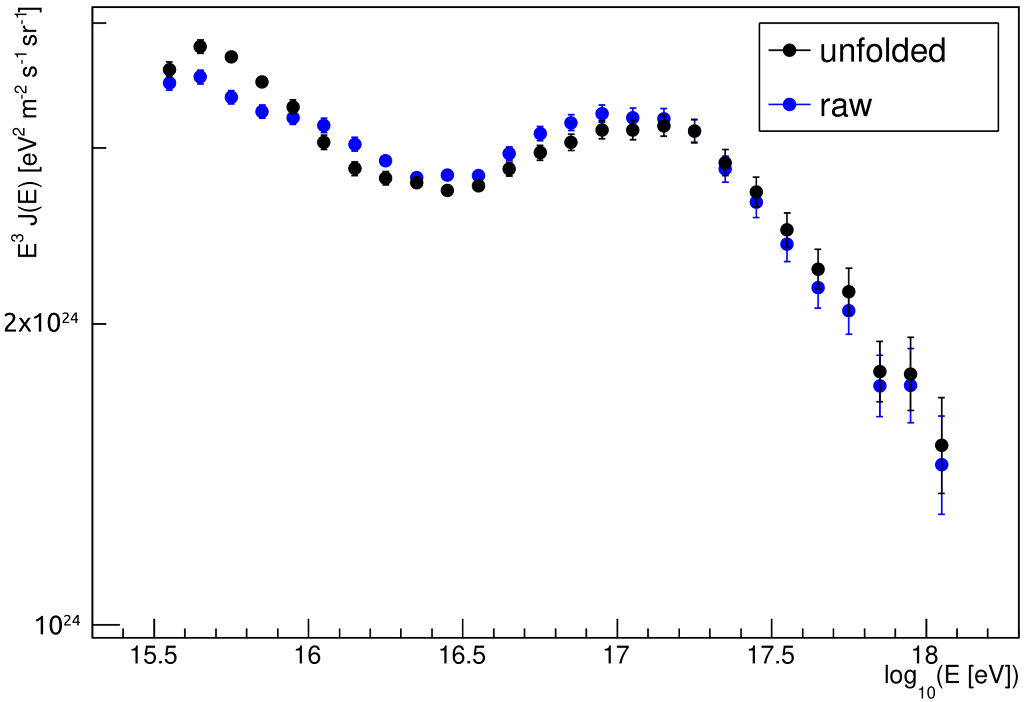
3x energies of breaks, 4x spectral indices, normalization

$$^{*}\, J(E) = J_0 \left(\frac{E}{E_{12}}\right)^{-\gamma_1} \prod_{i=1}^{3} \frac{1+\left(E/E_{i,i+1}\right)^{-\gamma_i}}{1+\left(E/E_{i,i+1}\right)^{-\gamma_{i+1}}}$$

Energy spectrum from Cherenkov-dominated data

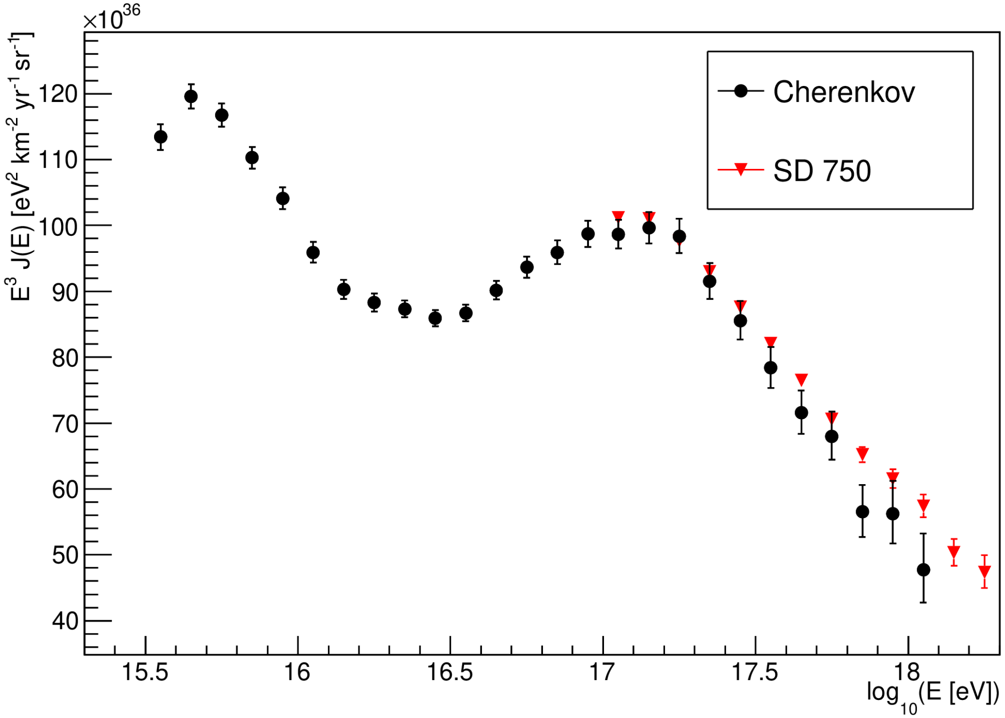
- **measurement of the 2nd knee at Auger**
- very good agreement with SD 750 spectrum

raw vs. unfolded



flux in logarithmic scale

comparison with SD 750

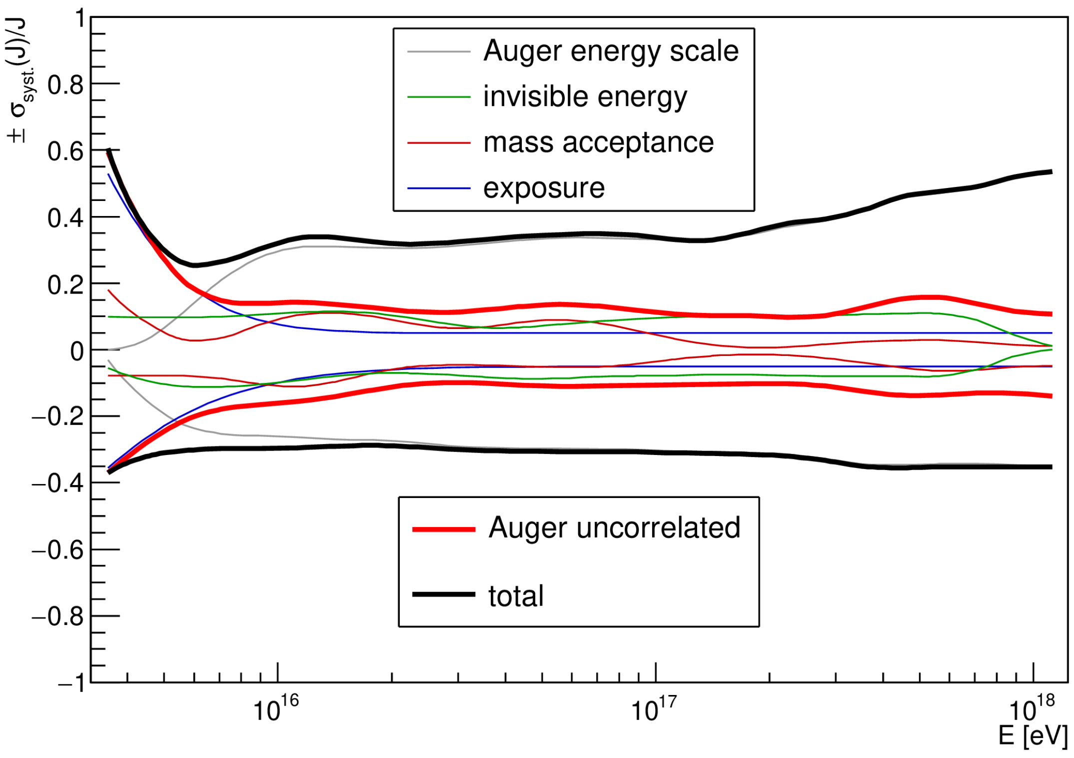


flux in linear scale

Systematic uncertainties

- **energy scale** – 15% in energy
  - most important is the uncertainty in absolute calibration of PMTs
- mass composition of CR
  - causes uncertainty in exposure
- **exposure**
  - dominated by energy scale uncertainty (secondary effect) – solved by fiducial volume cuts
- **total uncertainty in flux 30-60%**
  - dominated by propagated energy scale uncertainty

syst. uncertainties as ratios of the flux

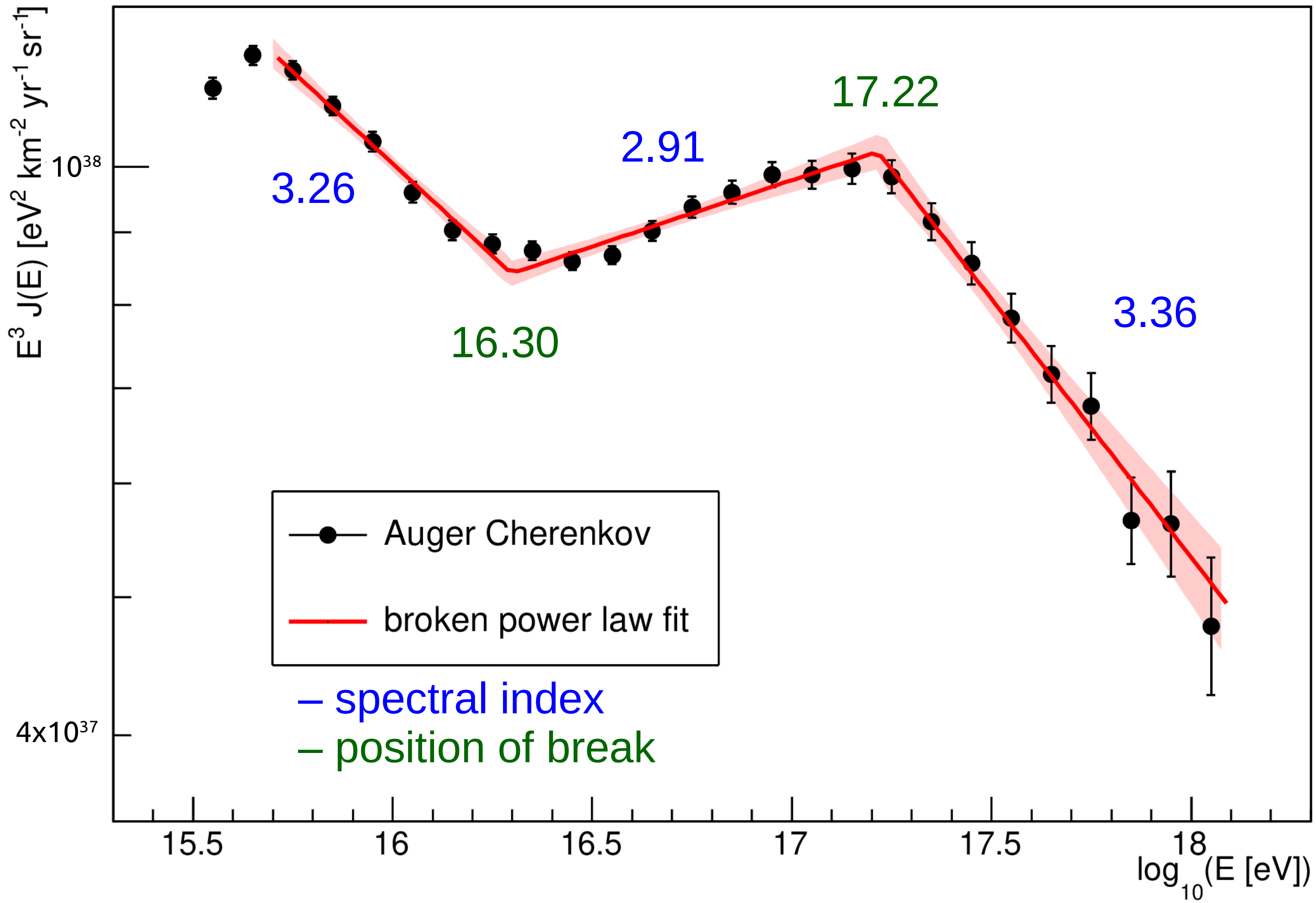


uncertainties in energy scale

Quantity	Uncertainty
FD calibration	9.9%
fluorescence yield	3.6%
Cherenkov emission model	3%
atmosphere	3.4%
FD profiles reconstruction	6.5%
FD energy bias	2.5%
energy scale stability	5%
invisible energy	4%
total	**15%**

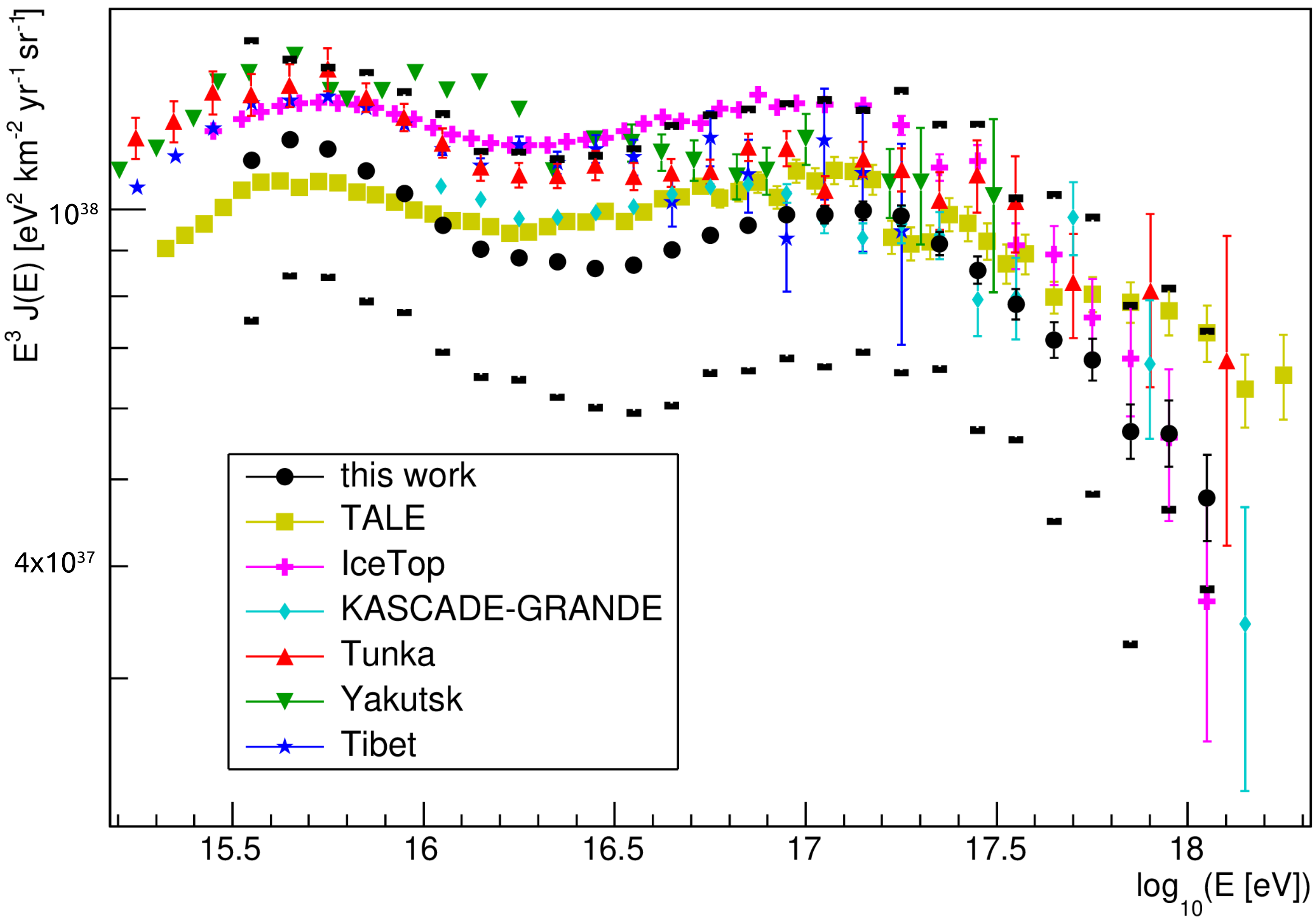
Characteristics of the energy spectrum

- **fit by broken power law function**
- red region at 95% CL
- 3 spectral indices, 2 breaks and normalization
- **2nd knee ~ $10^{17.2}$ eV**



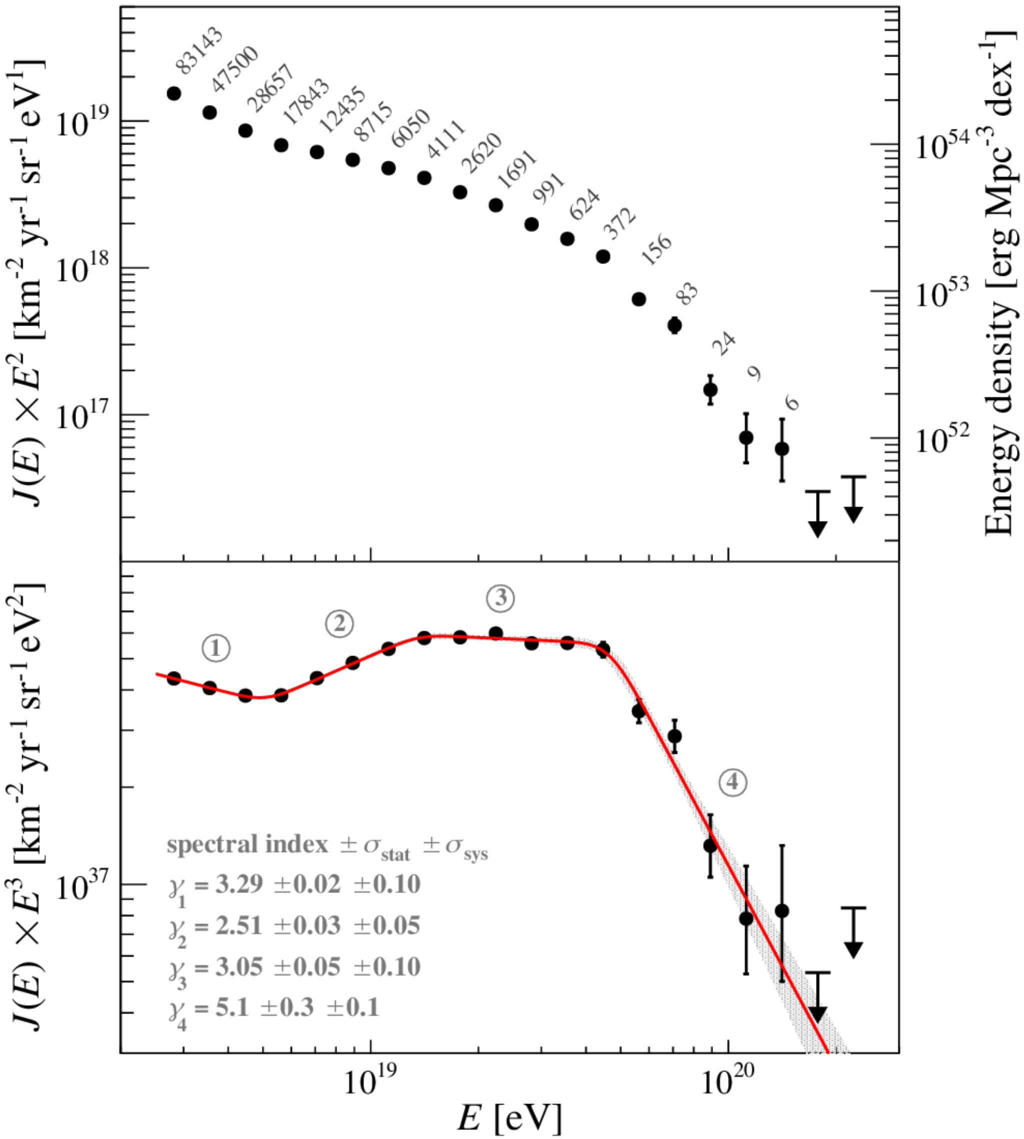
Comparison with other experiments

- **TALE** (Telescope Array) – FD telescopes, **similar method like Auger**
- surface arrays of Cherenkov/scintilator detectors
- non-imaging Cherenkov detectors
- 2nd vs. 1st knee ~ 1.6×10^{17} eV / 5×10^{15} eV ~ 31 similar to charge ratio Fe / p ~ 26
    - region interpreted as the end of the Galactic CR spectrum



Recent results at the highest energies

- **significant flattenig between 1.5x10^{19} – 5x10^{19} eV ③**
  - described as a smooth cutoff in the past

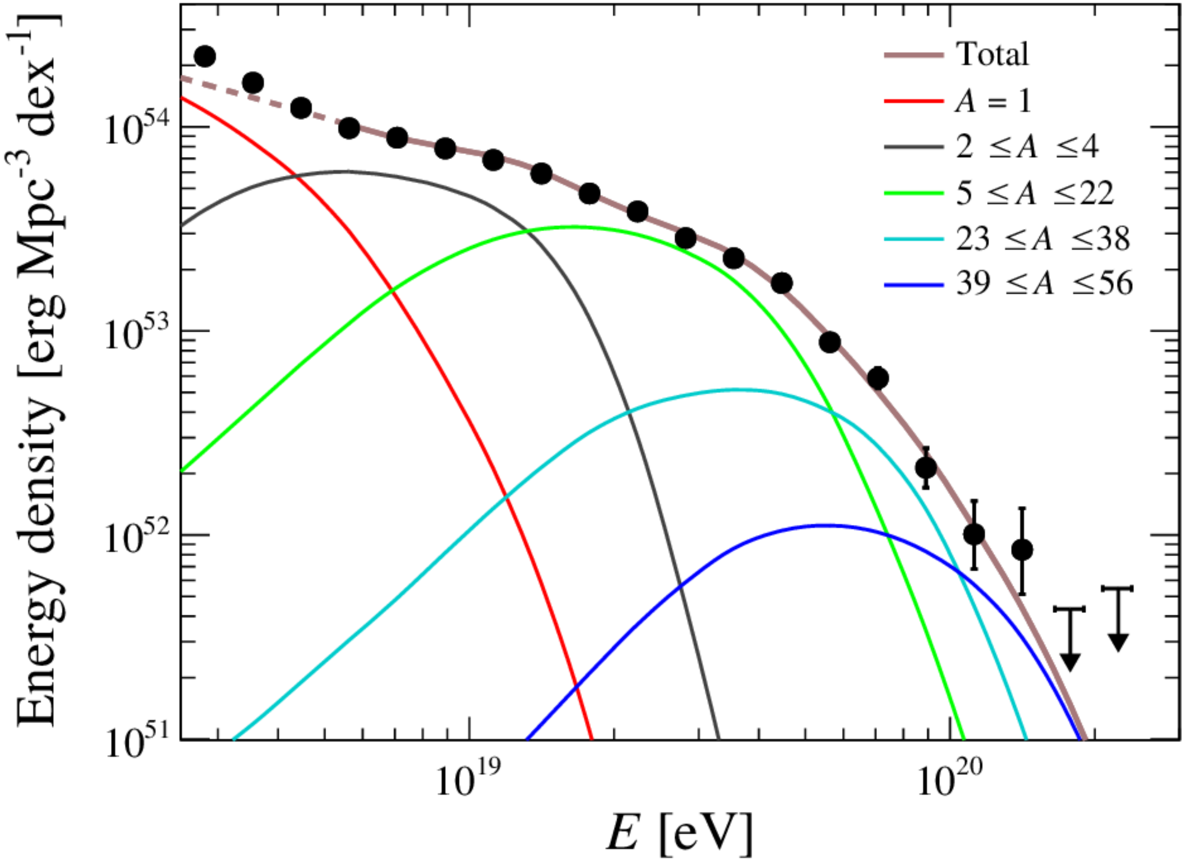


- 215 030 events in total
- exposure of 60 400 km^2 sr yr
  - energy independent

parameter	value $\pm\sigma_{stat.}$ $\pm\sigma_{sys.}$
J_0 [km^{-2}sr^{-1}yr^{-1}eV^{-1}]	$(1.315 \pm 0.004 \pm 0.400) \times 10^{-18}$
γ_1	$3.29 \pm 0.02 \pm 0.10$
γ_2	$2.51 \pm 0.03 \pm 0.05$
γ_3	$3.05 \pm 0.05 \pm 0.10$
γ_4	$5.1 \pm 0.3 \pm 0.1$
E_{12} [eV] (ankle)	$(5.0 \pm 0.1 \pm 0.8) \times 10^{18}$
E_{23} [eV]	$(13 \pm 1 \pm 2) \times 10^{18}$
E_{34} [eV] (suppression)	$(46 \pm 3 \pm 6) \times 10^{18}$
D/n_{dof}	17.0/12

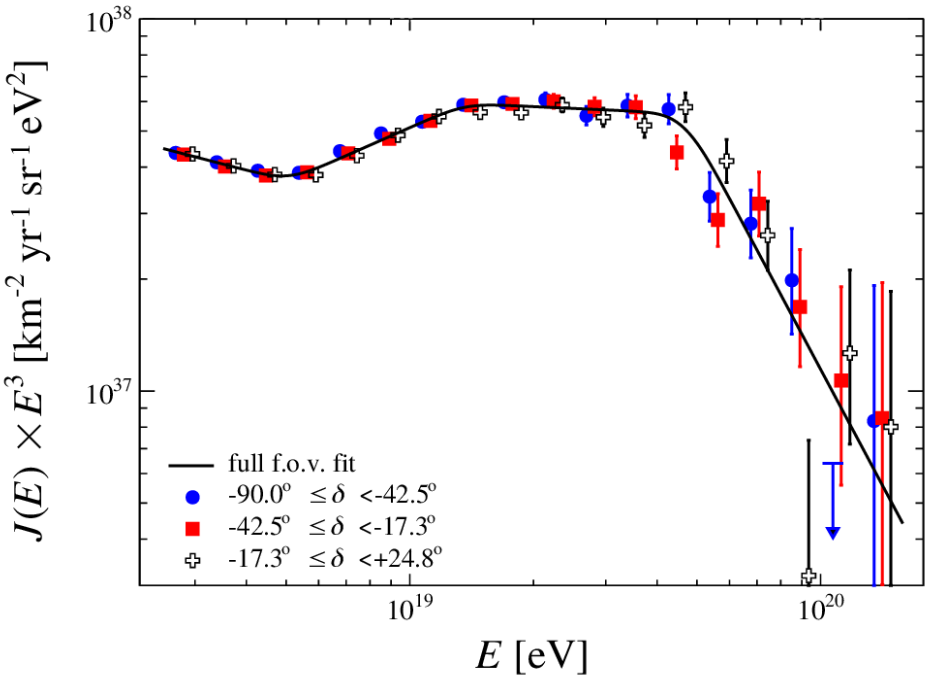
Recent results at the highest energies

- **combined fit of X_{max} distributions and spectrum**
  - contradicts pure proton scenario
  - includes propagation effects and source pars. - some freedom in model
  - steepening above $5x10^{19}$ eV from maximum energy of acceleration and GZK
  - steepening above 10^{19} eV from interplay between He and CNO - different injection energies and propagation

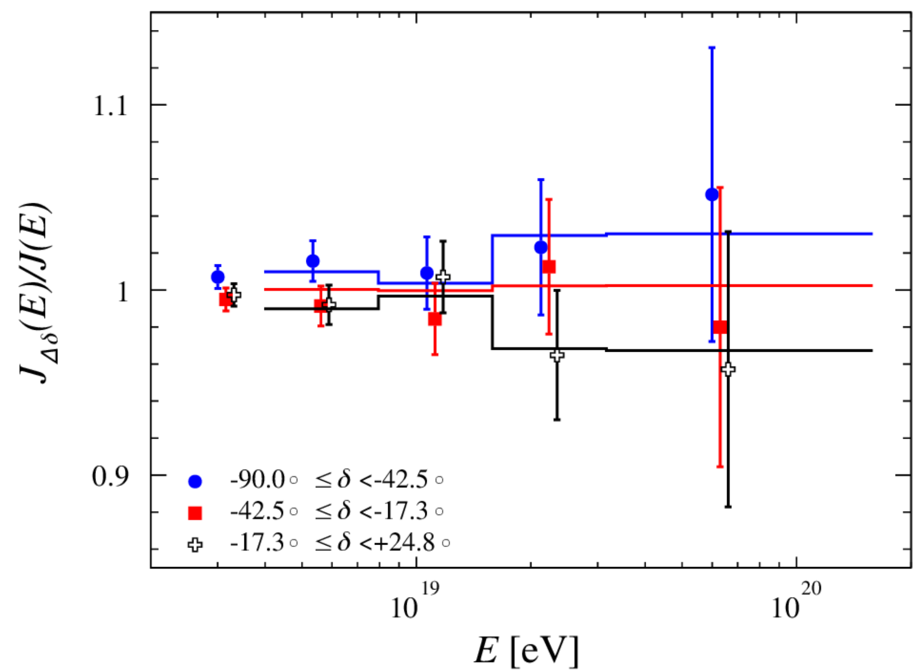


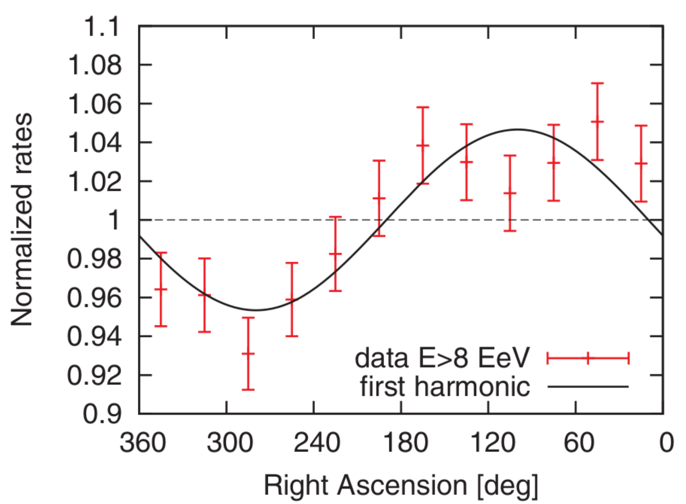
Recent results at the highest energies

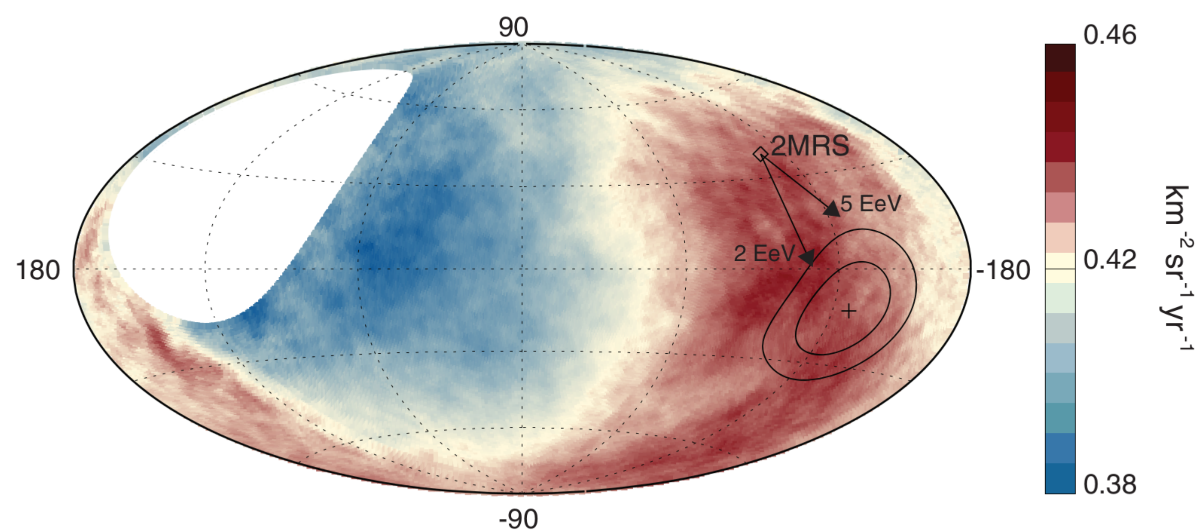
- **no declination dependence** except the one expected from the dipole contribution



expectation from dipole



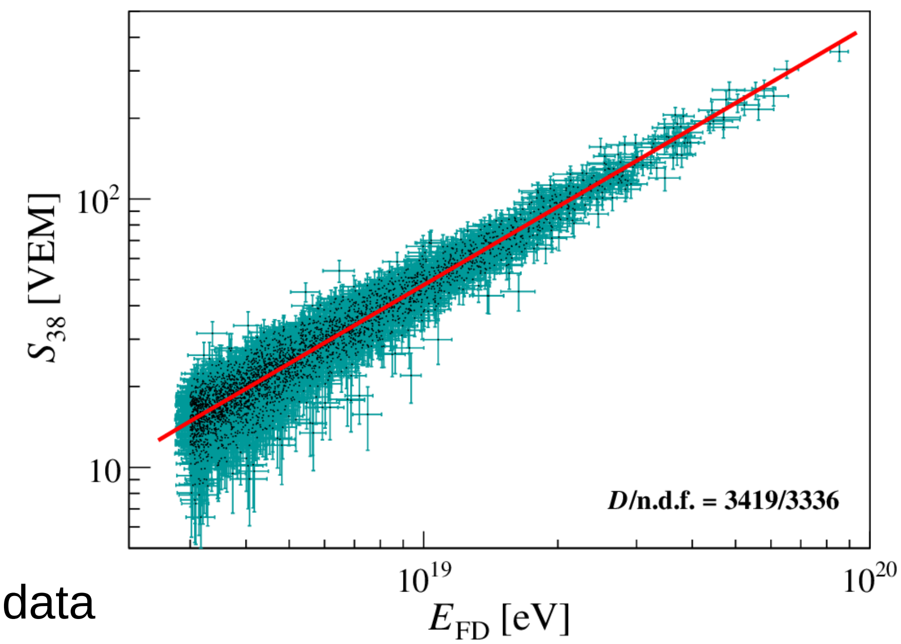




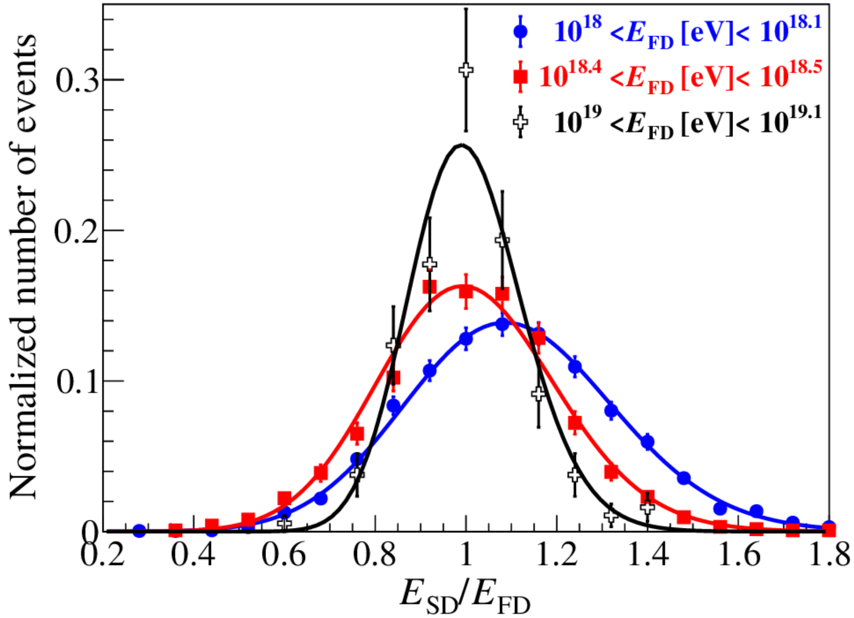
Recent results at the highest energies

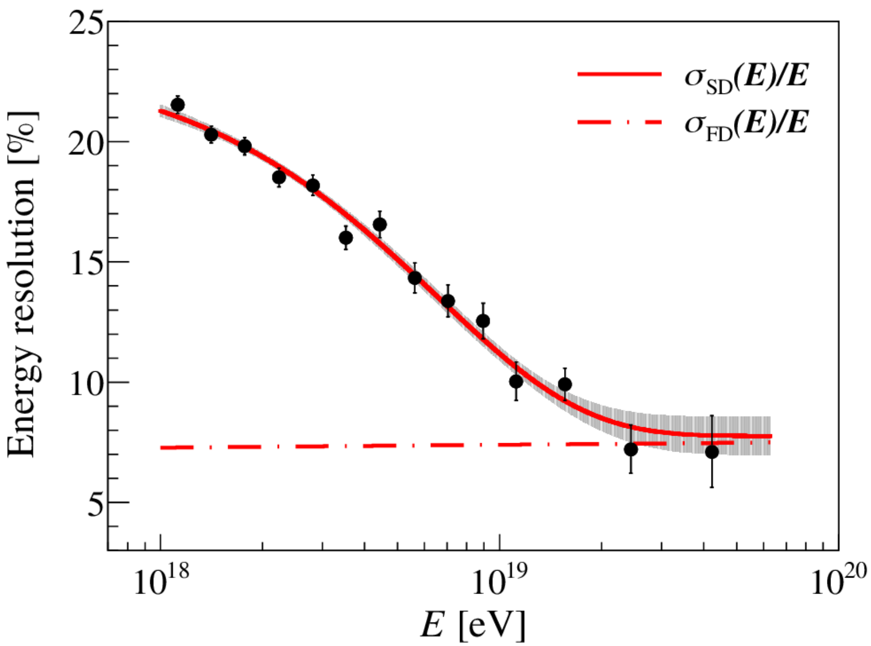
updated calibration

- focused on **energies above 2.5x10^{18} eV**
- SD vertical analysis from main array
- description of the detector needed also
  below full detection efficiency threshold
  - bin-to-bin migrations



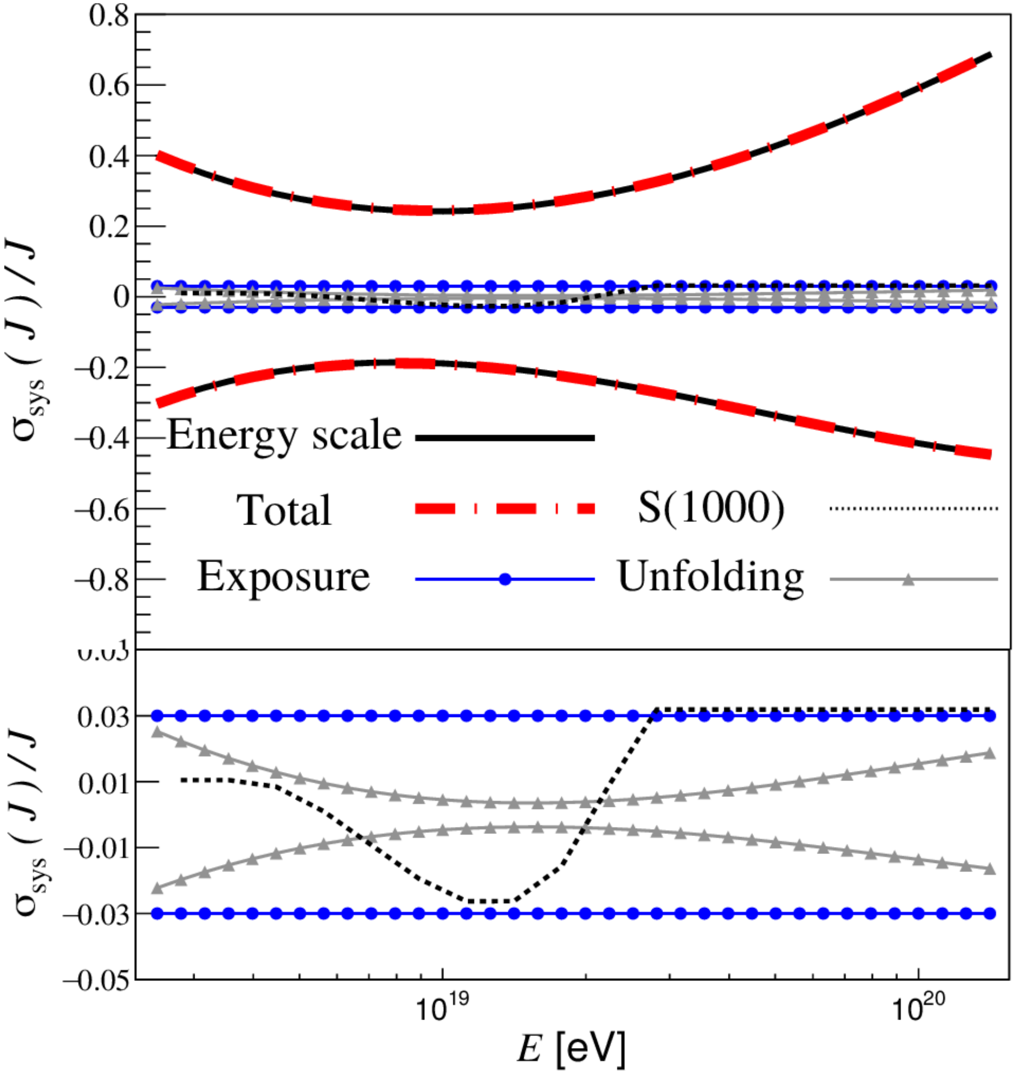
- energy resolution and biases estimated from data



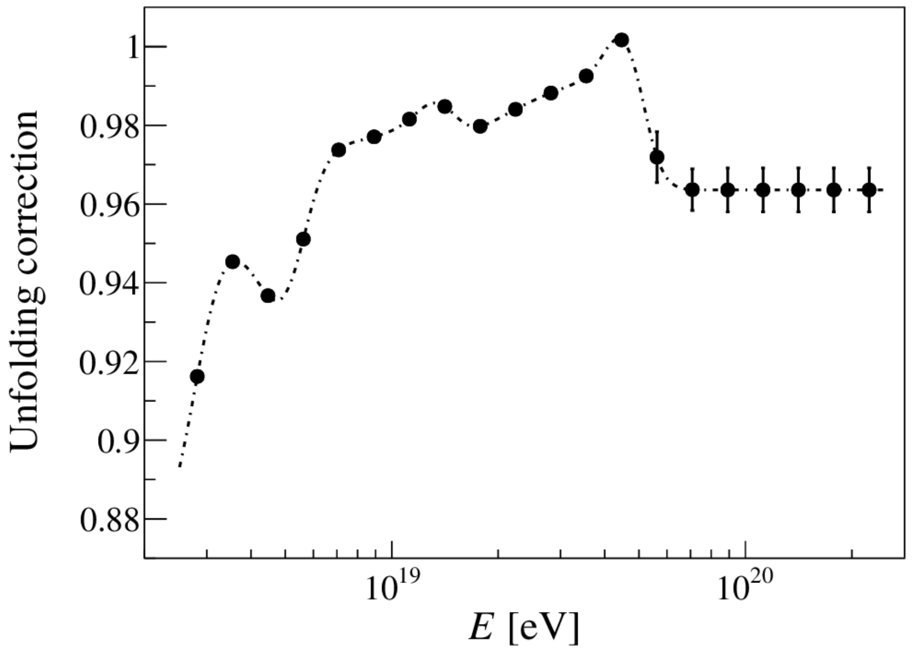


Recent results at the highest energies

systematic uncertainties



unfolding correction factors



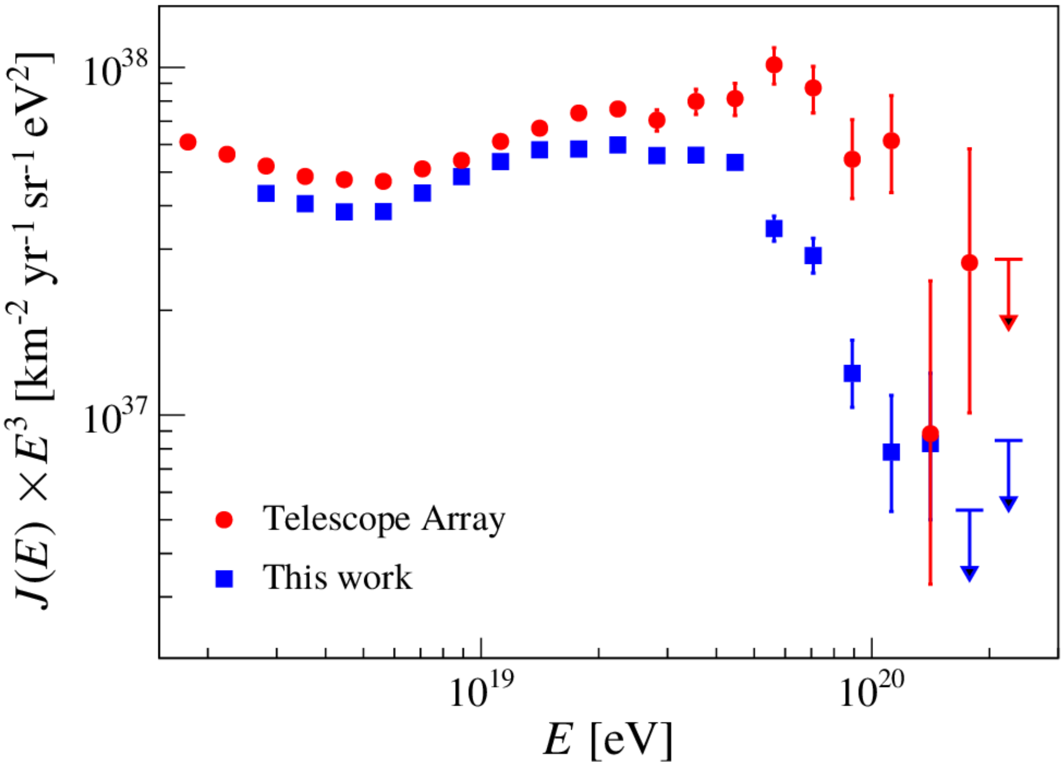
AugerPrime upgrade - ongoing

- goal is to **distinguish EM from muonic part** of the EAS signal in SD
    - possibility of mass-constrained anisotropy studies
    - better tests of HE hadronic interaction models
- **main upgrades:**
    - **scintilator detectors** atop of WCD stations
        - measurement of the EM part, WCD sensitive to both parts -> subtraction possible
        - useful for **vertical** showers (limited detection area of plate scintillators)
    - **radio antennas** attached to WCD stations
        - also measure EM part
        - useful for **horizontal** showers (larger radio footprint on the ground)
    - **extended FD uptime** with the use of low-gain setting
        - extend X_{max} measurements to higher energies

plus AMIGA in Infill - burried scintilators

Conclusions

- **Pierre Auger Observatory measures energy specturm of CR between $10^{15.5}$-10^{21} eV**
    - 5 methods used – Cherenkov, SD 750 Infill, hybrid, SD 1500 vertical, SD 1500 inclined
    - 5 breaks in energy spectrum + 6 spectral indices
- analysis of **Cherenkov-dominated data** covers the low energy range ($10^{15.5}$-$10^{18.1}$ eV)
    - **first measurement of 2nd knee** at Auger
- **new results at the highest energies**
    - flattening of the spectrum between 1.5×10^{19}-5×10^{19} eV
    - disagreement between TA and Auger spectrum at the highest energies still present

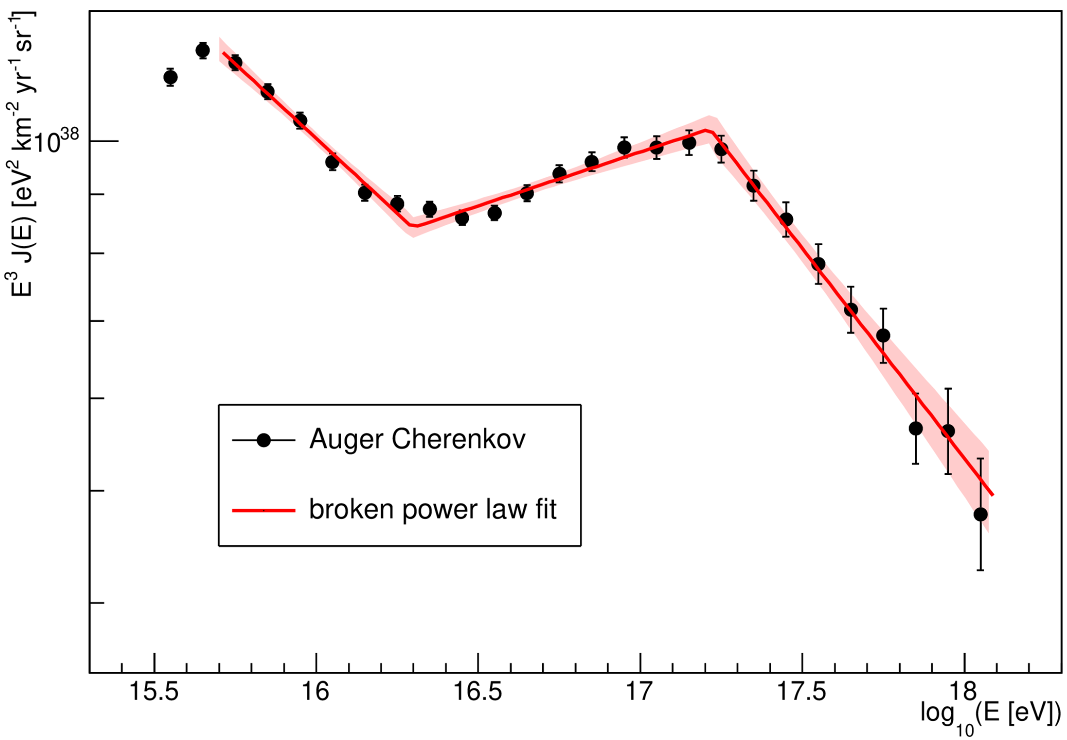


Backup

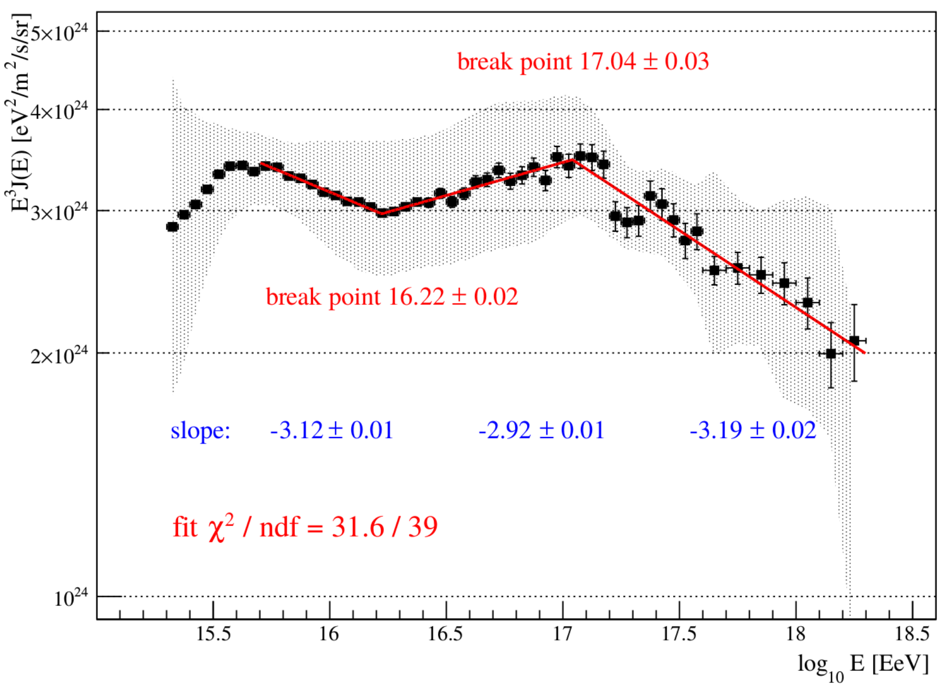
Low energy spectrum characteristics

fit parameters

Parameter	Value $\pm$ $\sigma_{\text{stat.}}$ $\pm$ $\sigma_{\text{syst.}}$
J_0 [km^{-2} sr^{-1} yr^{-1} eV^{-1}]	$(1.005 \pm 0.006 \pm 0.4) \times 10^{-10}$
$\log_{10}(E_1\ [\text{eV}])$	$16.30 \pm 0.02 \pm 0.3$
$\log_{10}(E_2\ [\text{eV}])$	$17.22 \pm 0.03 \pm 0.2$
γ_1	$3.26 \pm 0.02 \pm 0.2$
γ_2	$2.91 \pm 0.01 \pm 0.06$
γ_3	$3.36 \pm 0.03 \pm 0.2$



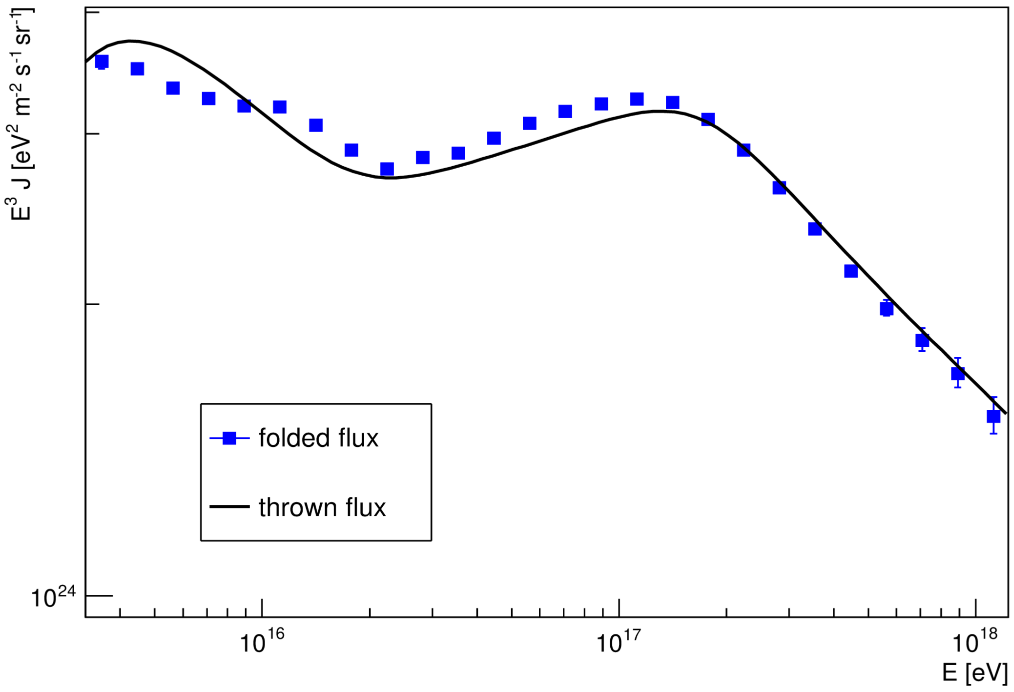
TALE Energy spectrum (Monocular)



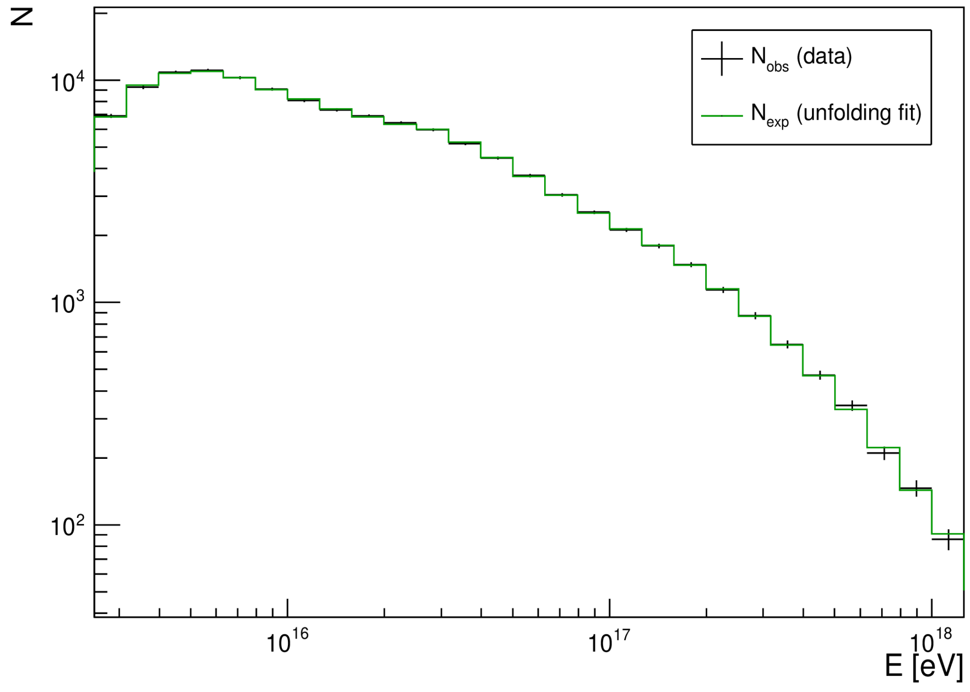
Correction for detector effects

- result of the forward folding fit

fitted function

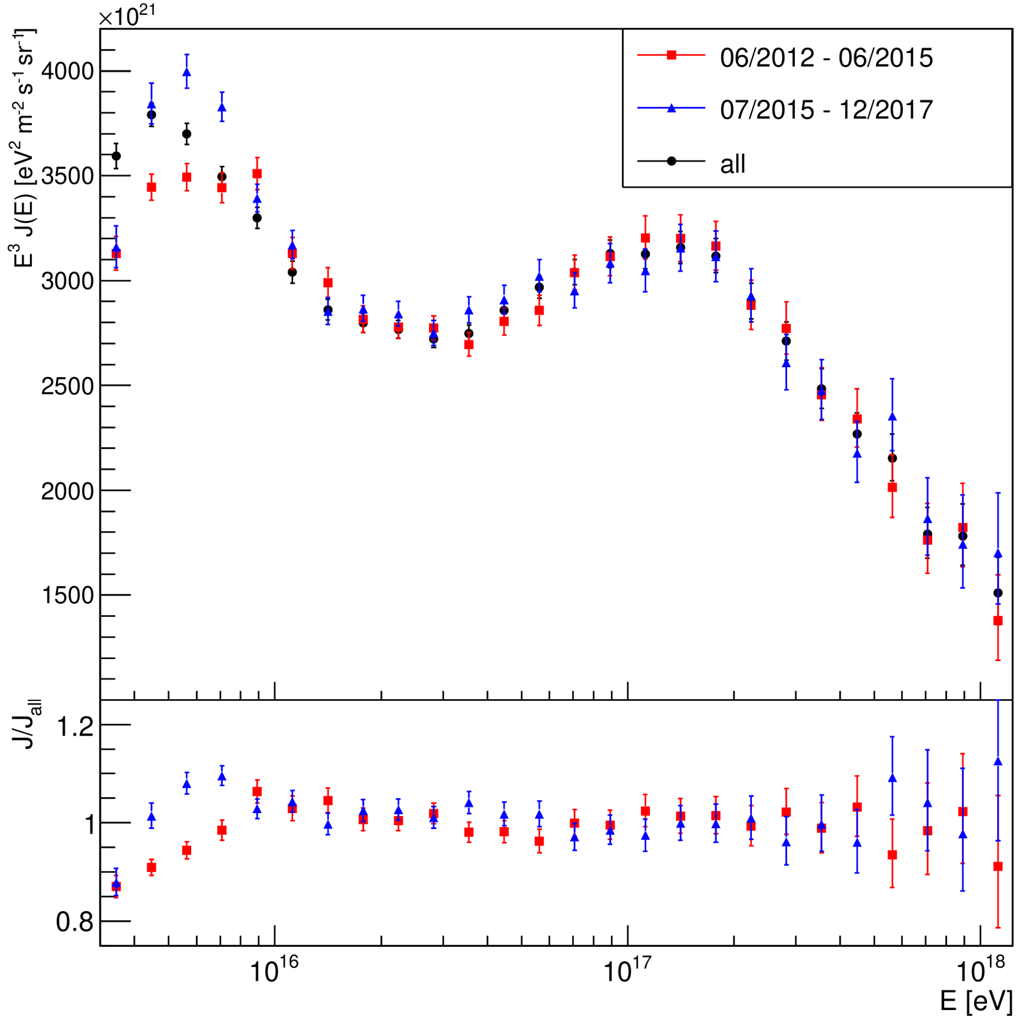


compatibility with the data distribution, $p_{\chi 2}$ = 0.68



Time stability

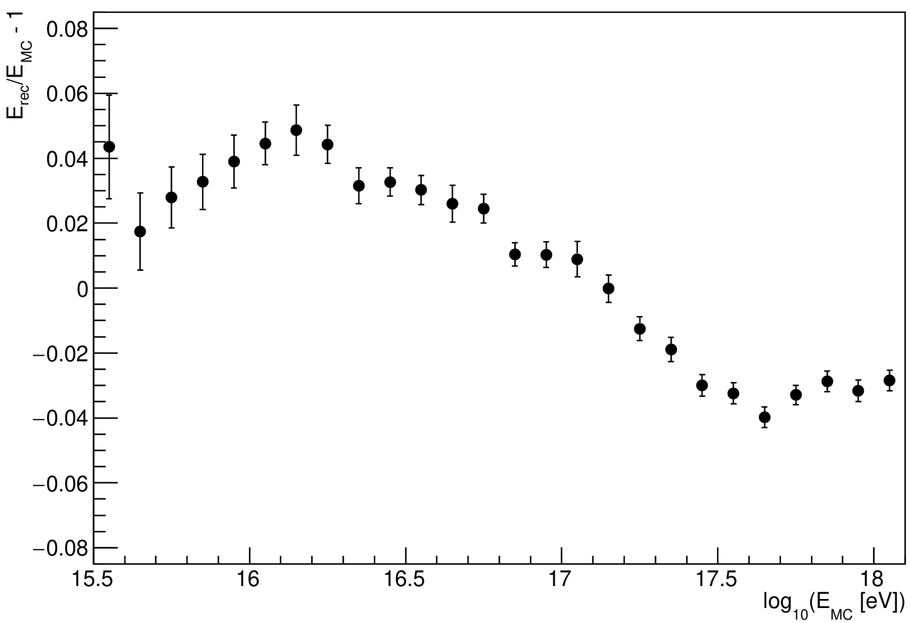
- two time periods with the same number of events
    - each has half of the total exposure
- difference below 10^{16} eV caused by increasing uncertainty in exposure?



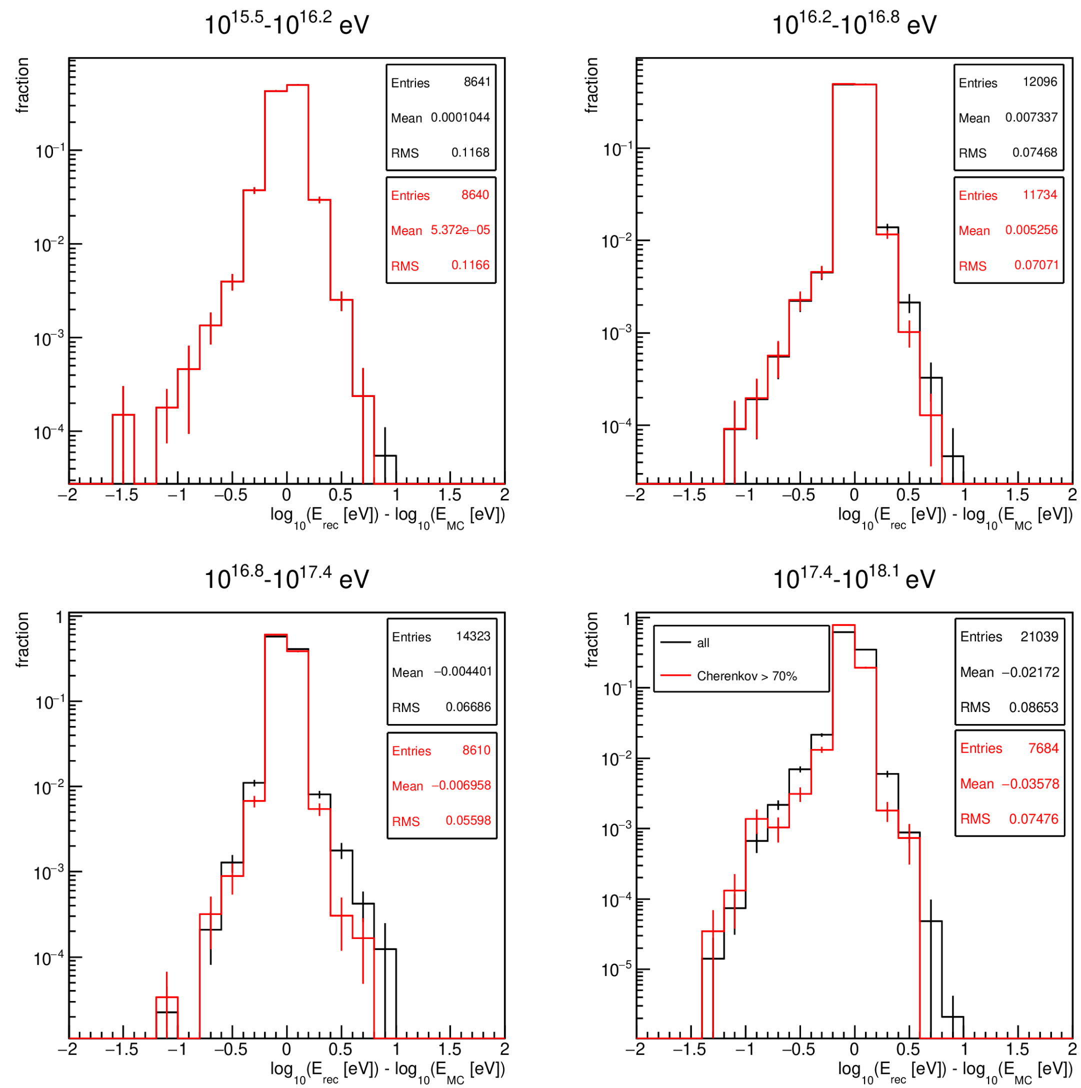
Precision of the energy reconstruction

Reflected in the migration matrix

bias < 5% in energy

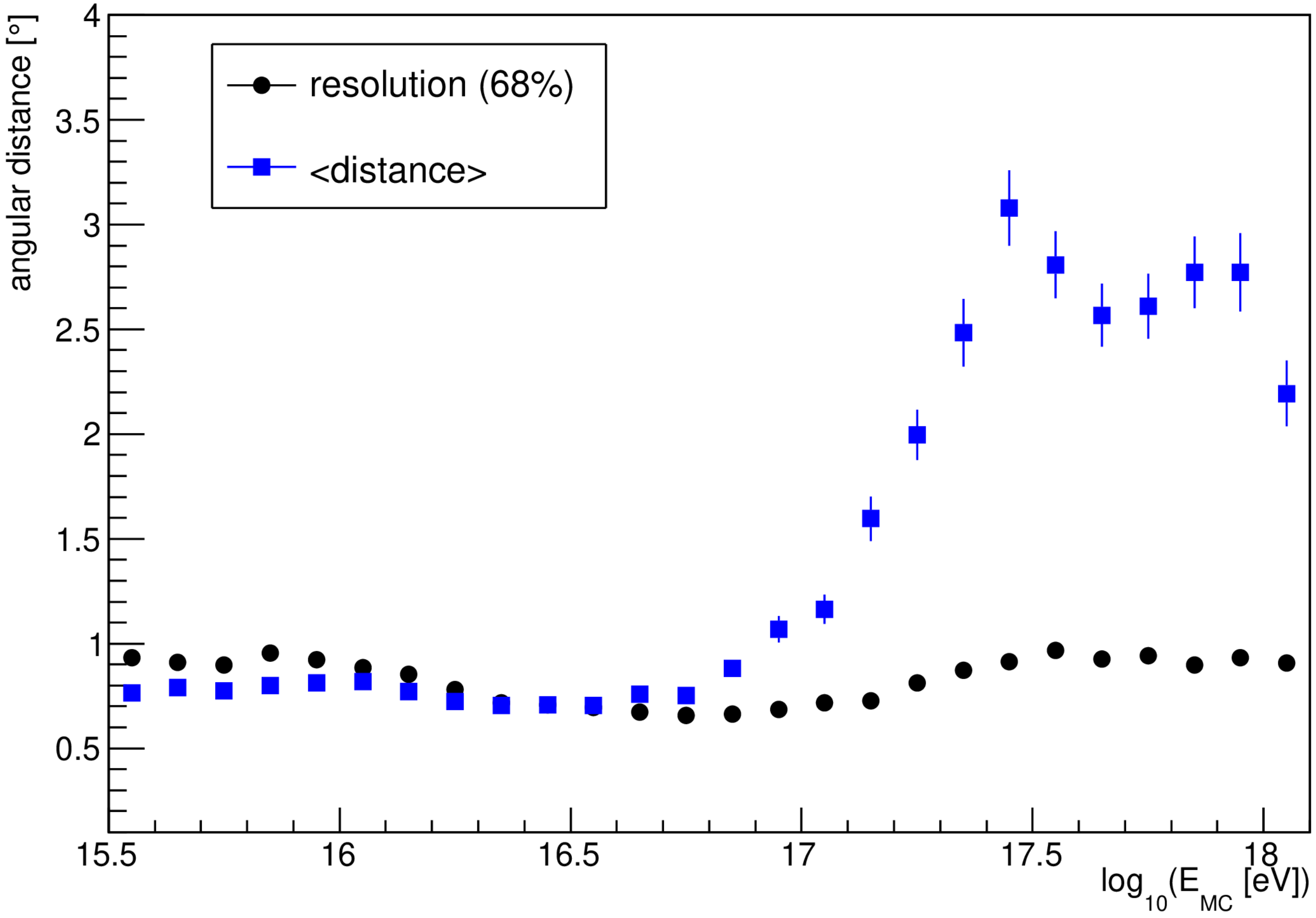


distribution of differences in $\log_{10}(E/eV)$



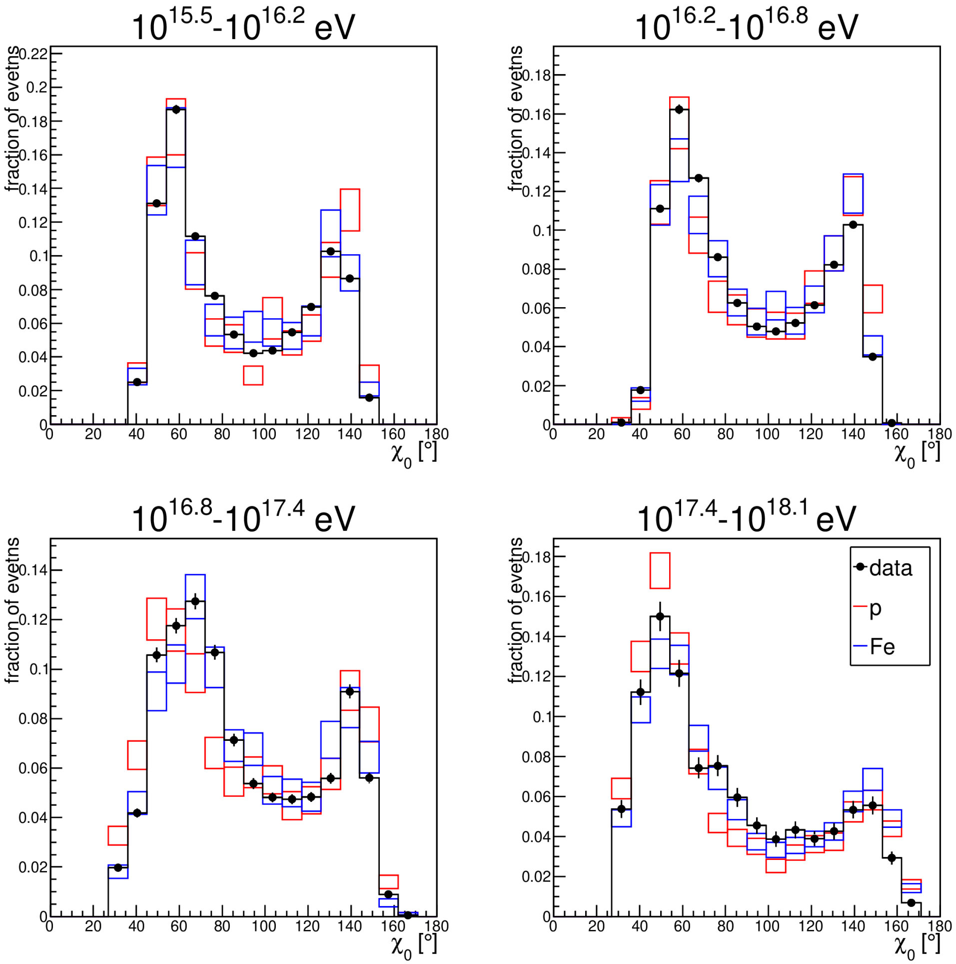
Angular resolution

- resolution better then 1°
- outliers at high energies - contamination by fluorescence events

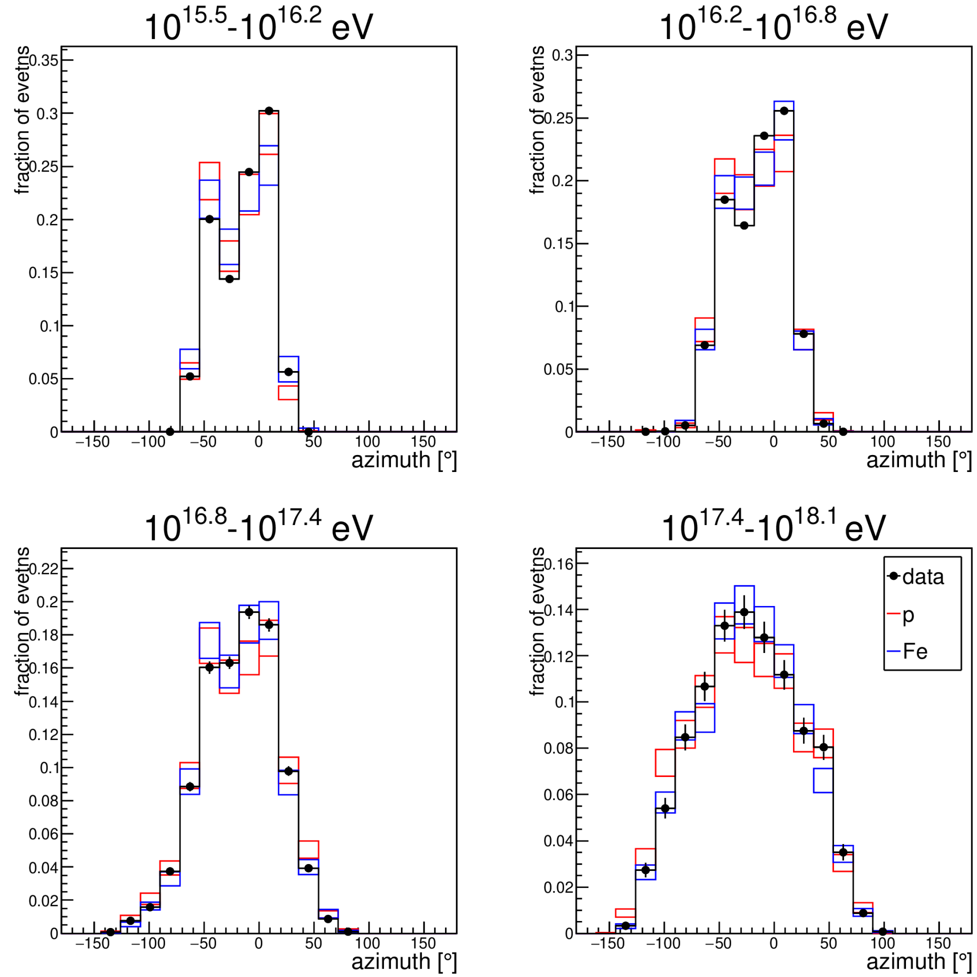


Compatibility of the MC and data

χ_0 parameter



azimuth



Invisible energy and muon problem

- invisible energy ~ energy in muons
- **muon problem - HE interaction models do not describe well muon numbers at high energies**
    - lower invisible energy in models is interpreted as a lack of muons in models

Fig. 3.2

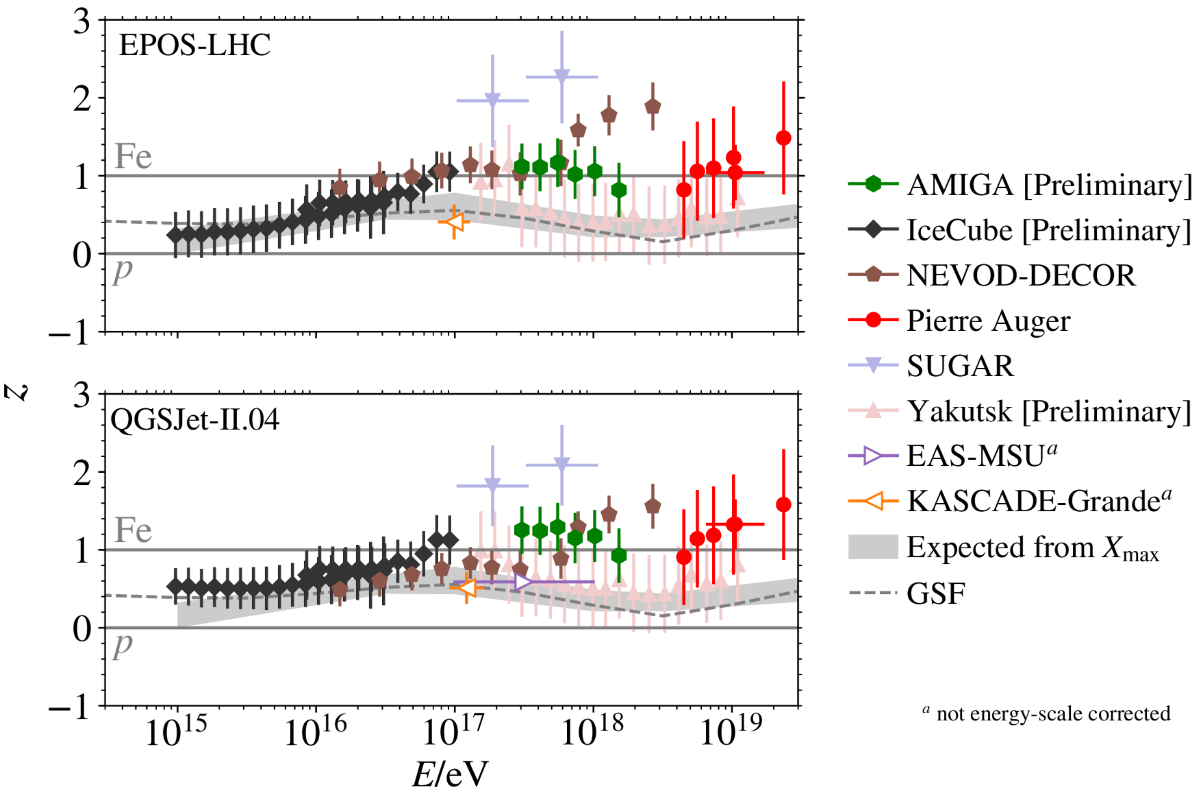
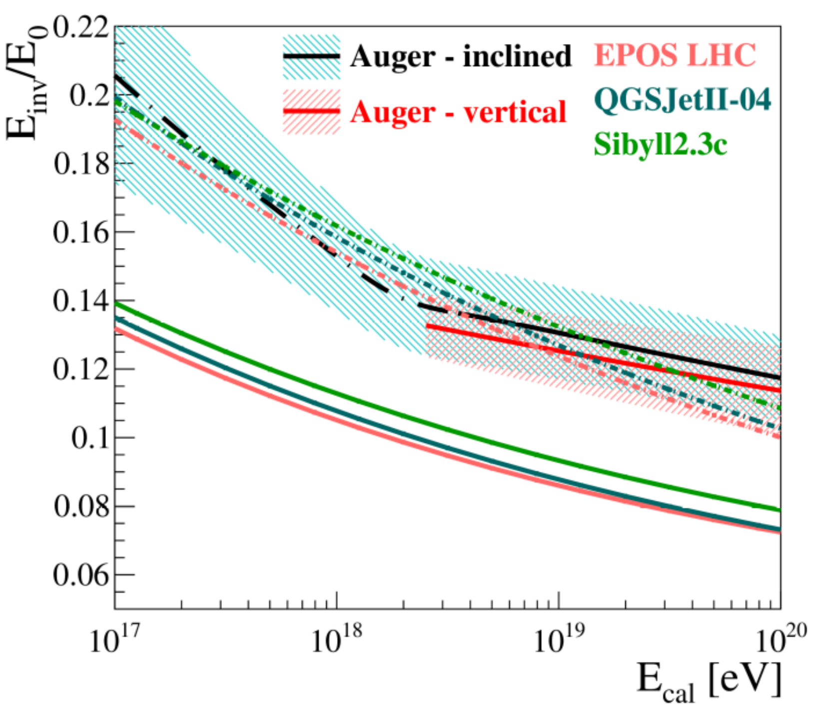
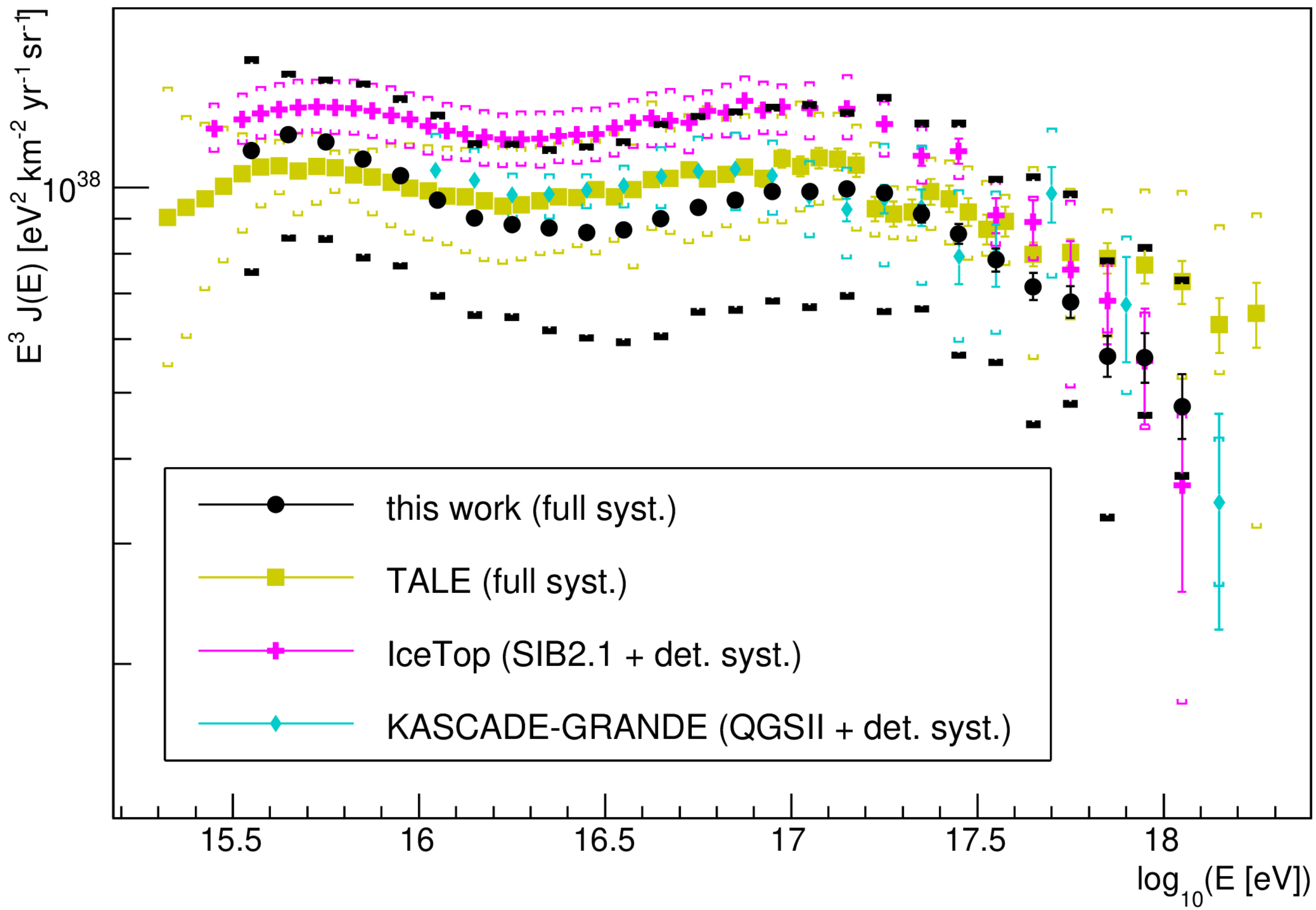


Fig. 3.1



Systematic uncertainties of other experiments

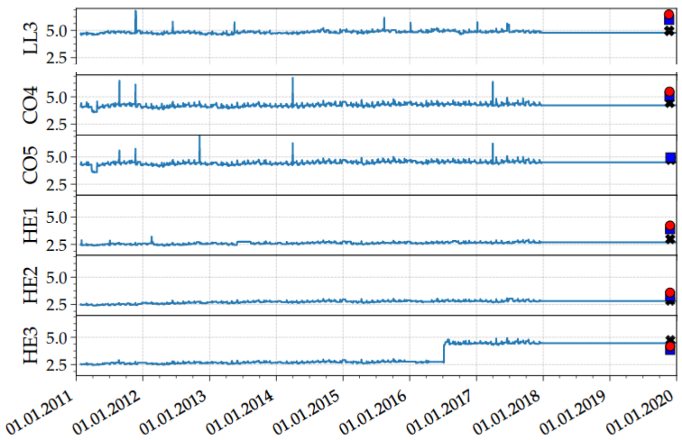


- IceTop and KASCADE-GRANDE - HE interaction model dependent
    - add ca. 30-40% (and no model describes showers well)
- Yakutsk - 32% in energy
- Tibet - „few tens of %“
- Tunka does not present any value

Outlook of Cherenkov spectrum publication

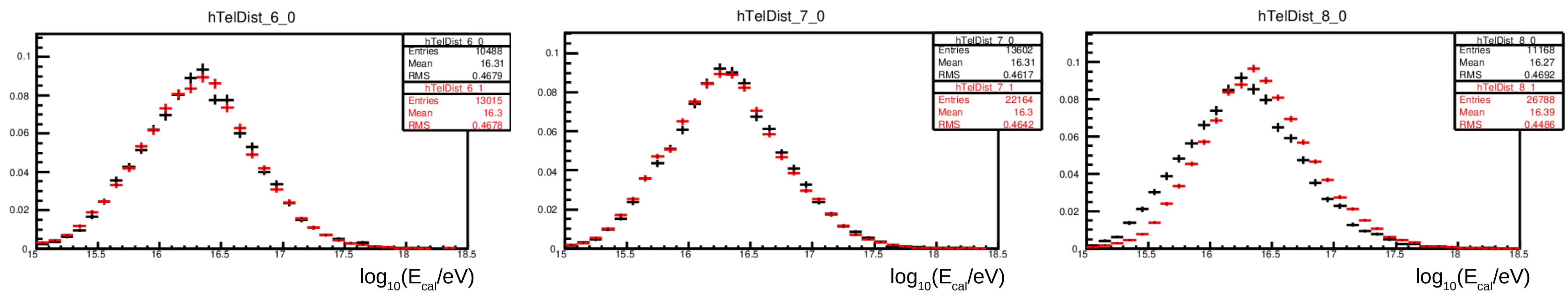
- presented at ICRC 2019 above $10^{16.5}$ eV
- troubles with calibration of HEAT tel. 3
    - to be solved by ongoing XY-scanner calibration campaign
    - tel. 3 currently removed from Cherenkov analysis

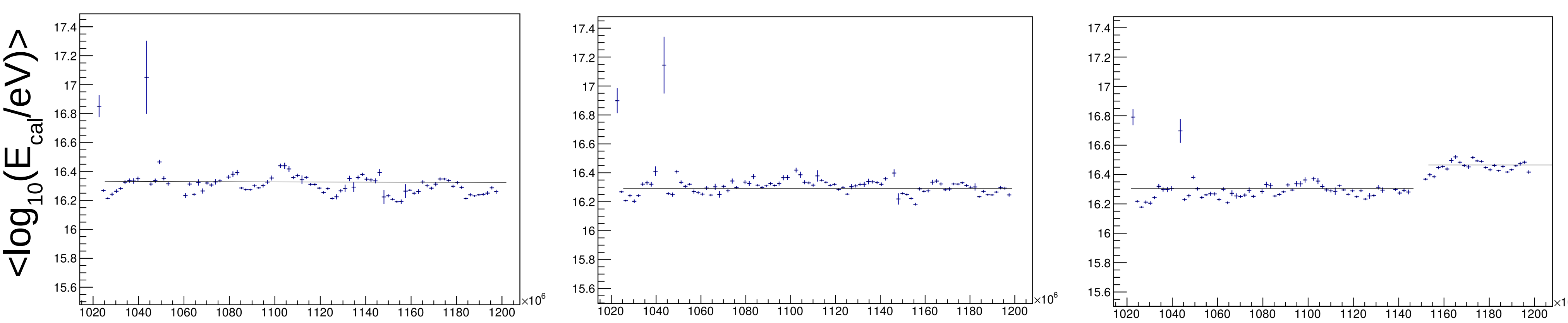
Absolute Calibration



Christoph Schäfer, Auger OCM, April 2020

first/second half of the data

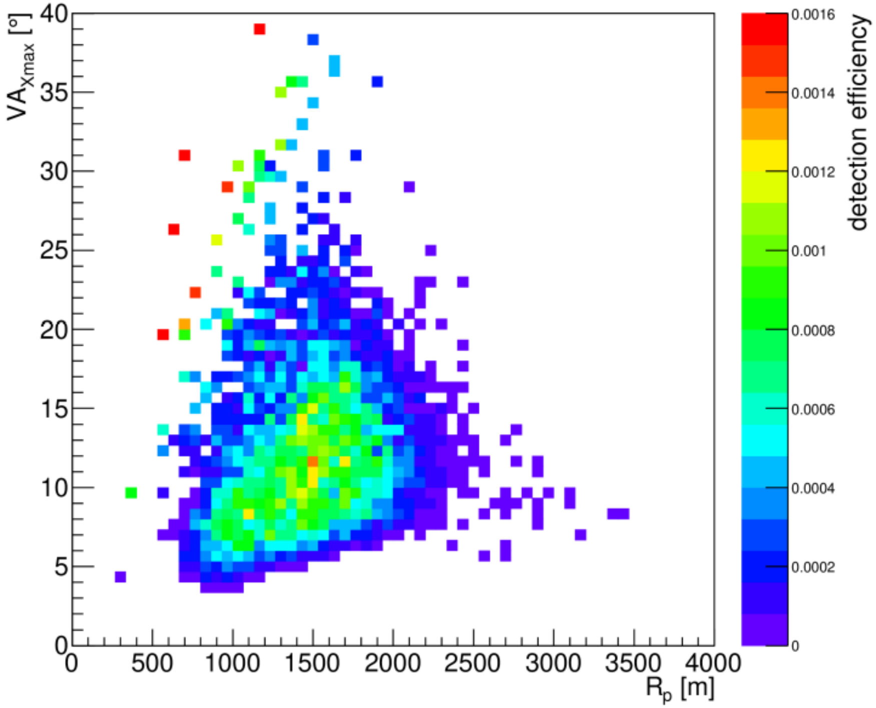


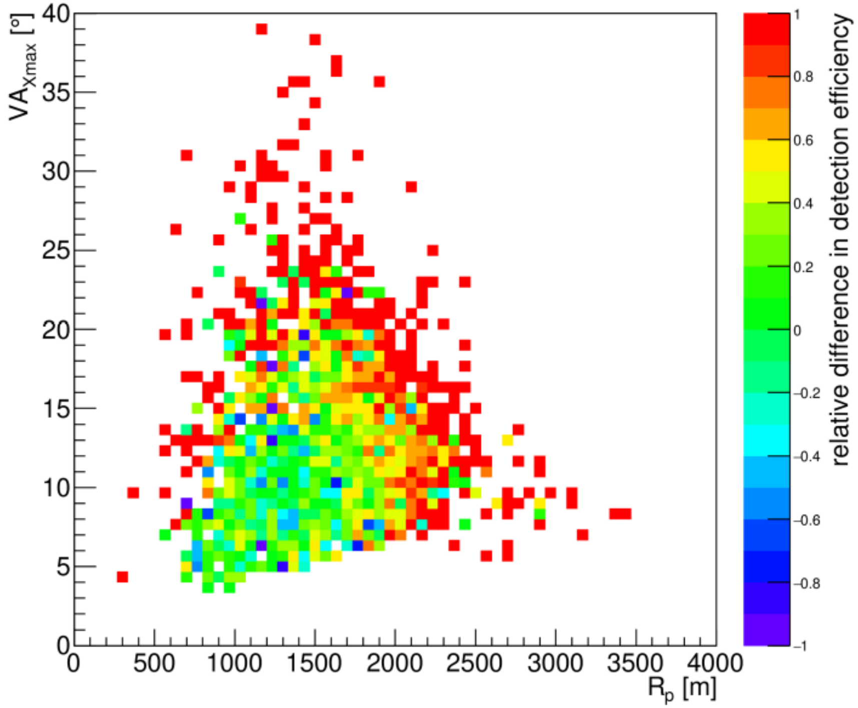


Fiducial volume cuts

- a change in the energy scale changes the evaluation of simulated exposure
- epsilon = detection efficiency = trigger + selection efficiency = N_{det}/N_{MC}
- use only sims/data that would be detected regardless of the energy scale -> no change in exposure
    - energy scale changes within its systematic uncertainty (15%)

$$(\Delta\mathcal{E})_i = 1 - \frac{\mathcal{E}_{i-1}}{\mathcal{E}_i}.$$





Fiducial volume cuts

cuts on R_p and VA_{Xmax}

effect on exposure