Measurement of the energy spectrum of cosmic rays above 10^{18} eV using the Pierre Auger Observatory.

arXiv:1002.1975v1

Outline

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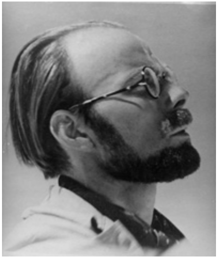
1. General background
2. Detection and Analysis
   - Detectors
   - Analysis
3. Results and conclusions
   - Conclusions

General Background



- The Ultra High Energy Cosmic Rays (UHECR), are the most energetic and rarest of particles are studied in Pierre Auger. Billions of secondary particles (shower) are produced when they strike the atmosphere.
- Flux of UHECRs exhibits:
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  2. Break in power law (ankle) observed $\approx 4 \times 10^{18}$ eV

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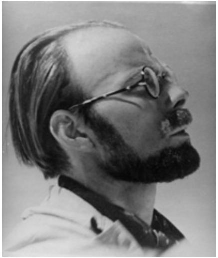

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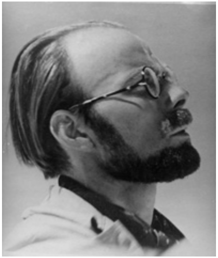

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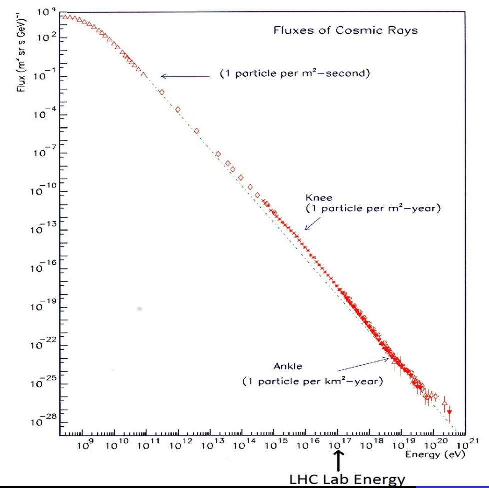

- Spectrum defined by broken power law.
- Knee at $E \sim 4\ PeV$.
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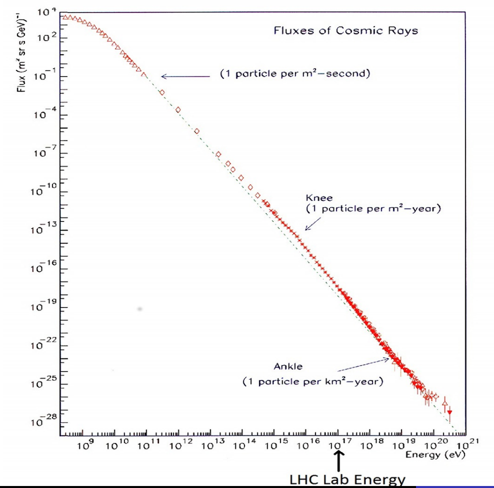

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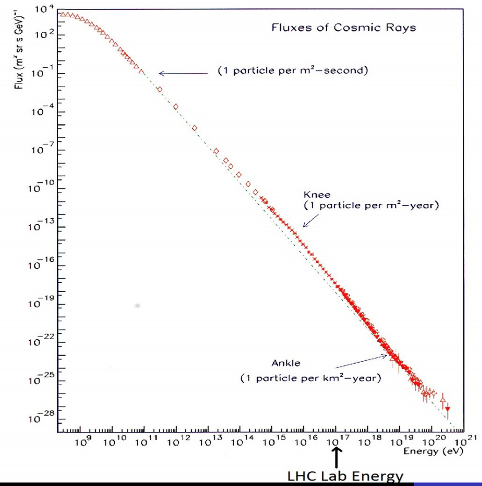

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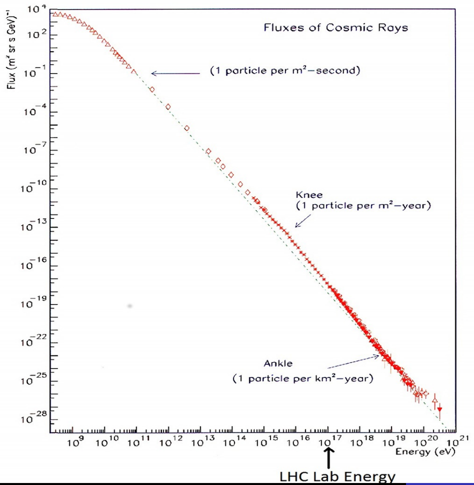

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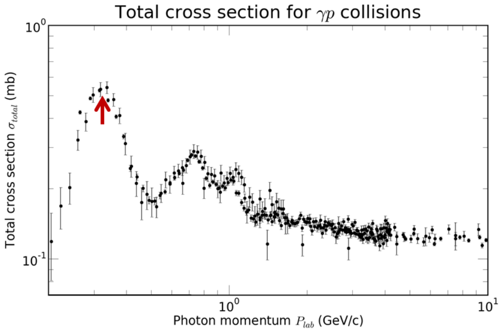

Taken from PDG

- Greisen-Zatsepin-Kuzmin cutoff is the result of photo-pion production.
- Main process: proton collision with Cosmic Microwave Background (CMB) photon.

$$p\gamma \longrightarrow (\Delta^+) \longrightarrow \pi + N$$

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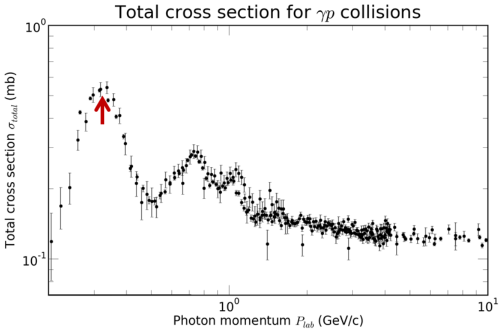

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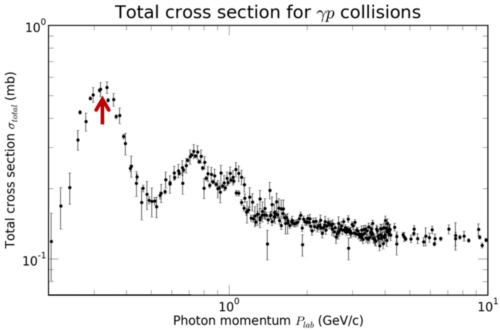

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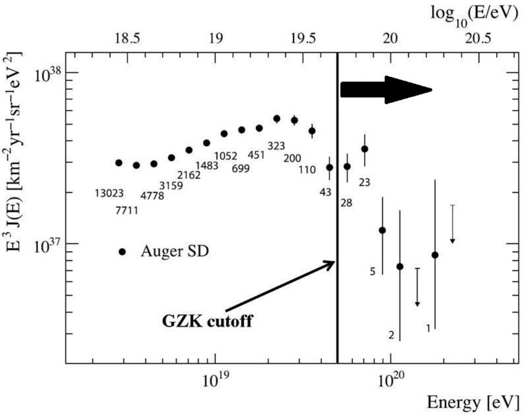

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- Proton energy loss leads to cutoff at 10^{20} eV.
- Mean interaction length $\approx 10 Mpc$.
- "GZK Horizon" at 50 Mpc, no 10^{20} eV particles past this distance.

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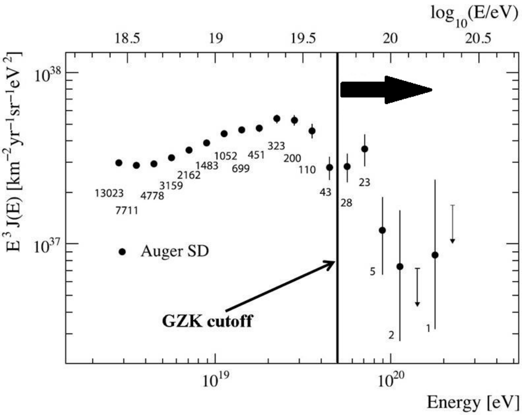

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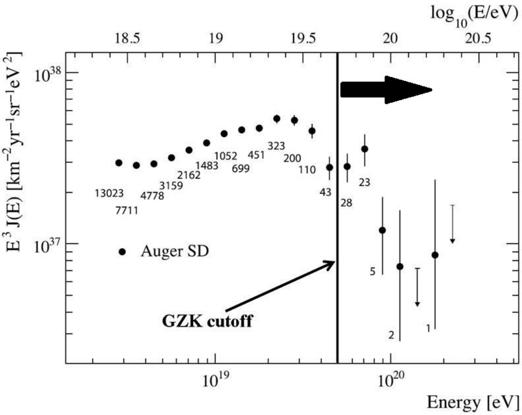

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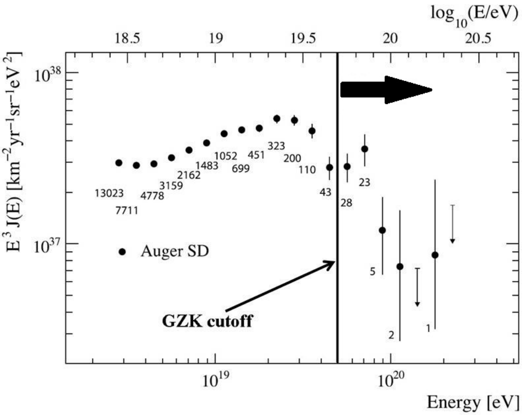

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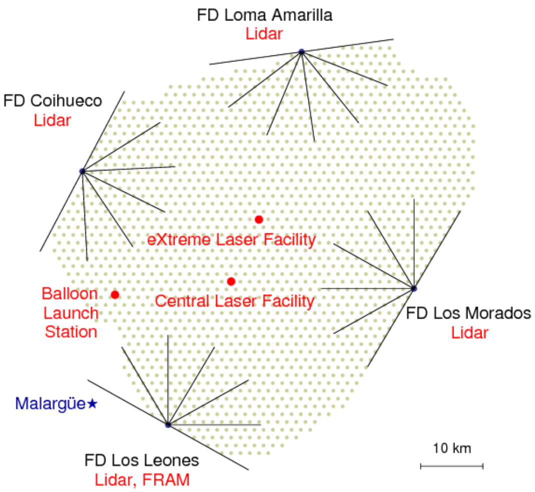

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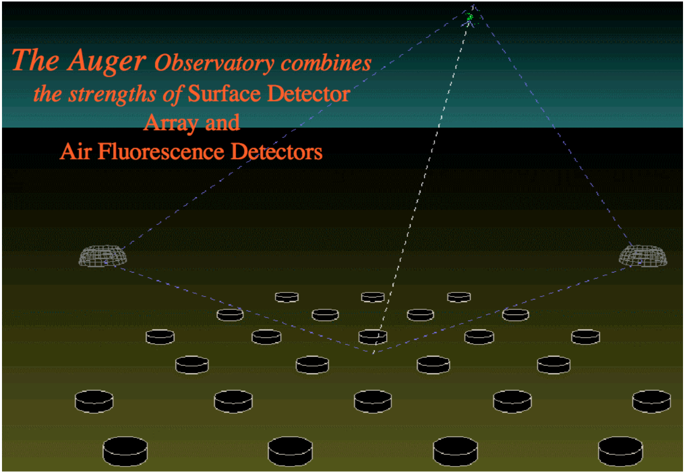
The Detectors of Pierre Auger Experiment



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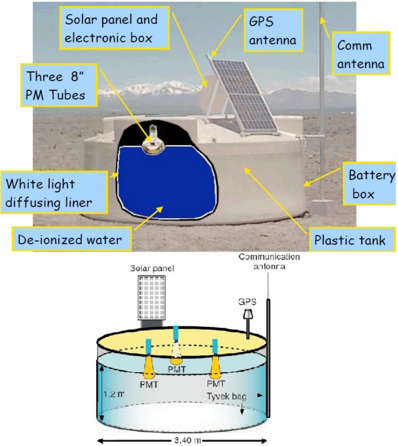
The Surface Detectors (SD) (general information)



Taken from www.lip.pt/~jespada/Research/PAO.php

- 1600 water-Cherenkov detectors, distributed over $3000\ km^2$, spaced $1.5\ km$ on a triangular grid.
- Dimensions: 3.6m diam $\times$ 1.5m height.
- 12 tons of pure water per tank.
- 3 PMT detectors per tank, distributed symmetrically from center of tank.

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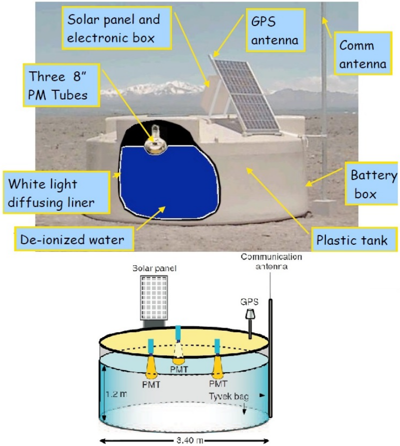

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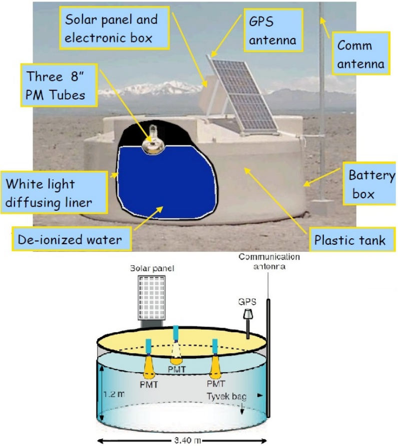

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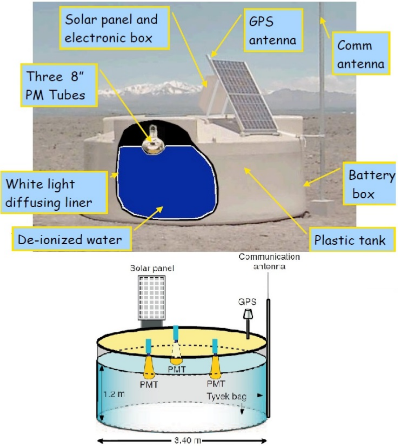

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- Five triggers.
- T1 (local): Time-over-threshold (ToT).
- T2 (local): Single threshold.
- T3 (array): Coincidence in > 3 stations which passed the T2 trigger.
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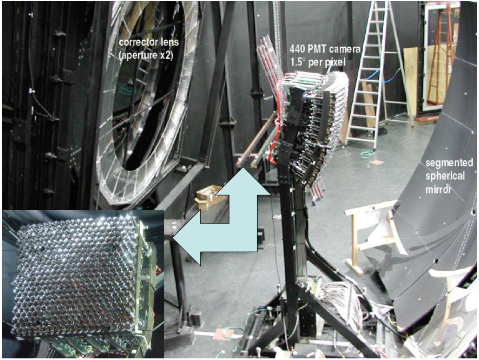

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- Measure the longitudinal profile of the shower dE/dX. (calorimetric)
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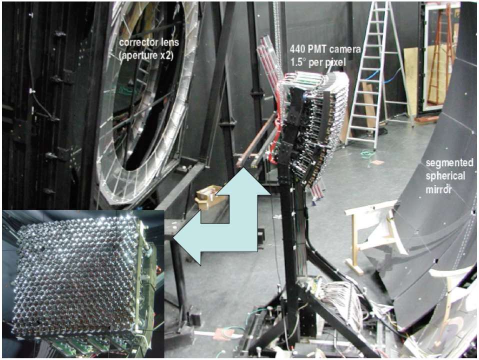

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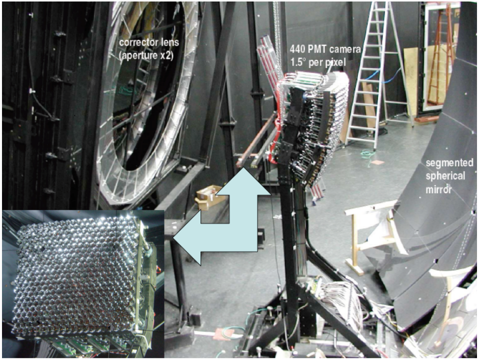

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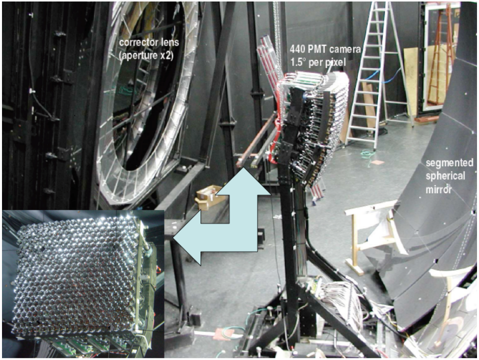

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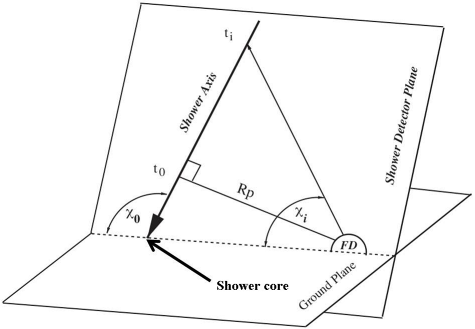
Detection of the Shower-Detector Plane (SDP)



Taken from Nuclear Instruments & Methods in Physics Research, Properties and performance of the prototype instrument for the Pierre Auger Observatory (2003)

- Uncertainty in SDP $\sim 0.1°$.
- Timing information of SD and FD used.
- Shower parameters (R_p, χ_0) are determined by fitting the timings and angles for all detectors to the functional form:

$$t_i = t_0 + \frac{R_p}{c} tan\left(\frac{\chi_0 - \chi_i}{2}\right)$$

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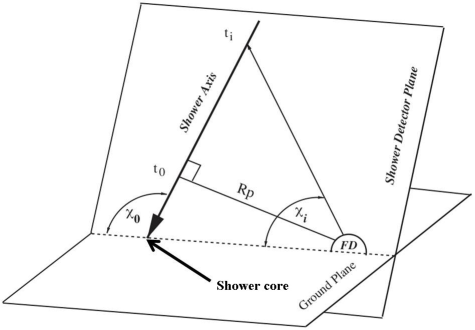

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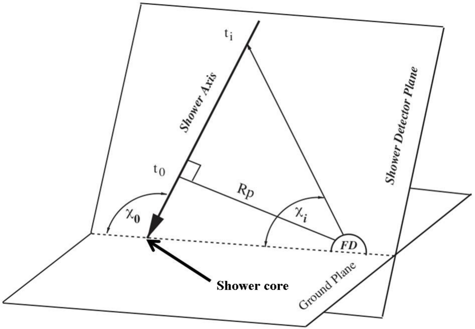

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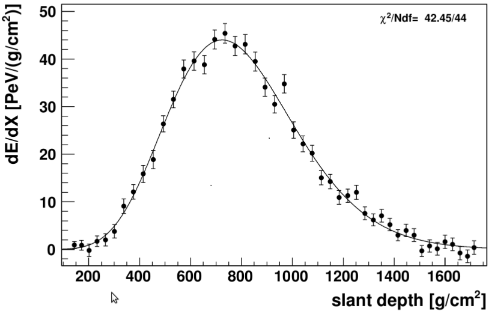
Energy reconstruction



Taken from The Pierre Auger Collaboration, arXiv:0907.4282v1 [astro-ph.IM]

- slant depth $$X^{\mu} = \int_{z}^{\infty} \rho(z')dz'$$
- The shower profile dE/dX is fitted to a Gaisser-Hillas function.
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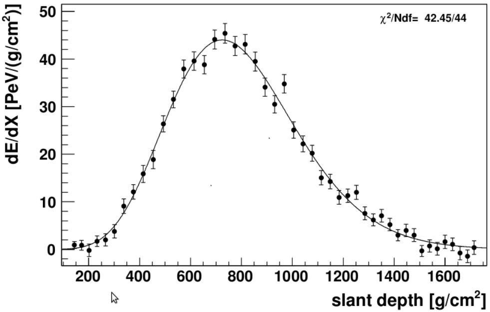

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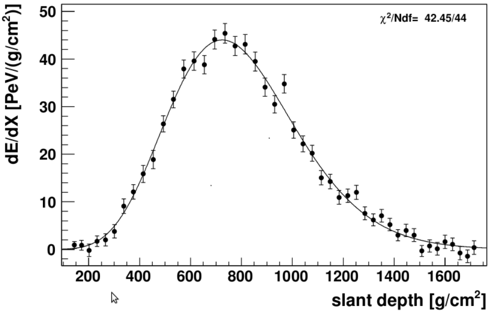

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Event Selection and Reconstruction

- Reconstructed showers with zenith angle $< 60^\circ$ and core must be within 1500 m of the station used for the geometrical reconstruction.
- Cherenkov light must contribute less than 50% of the overall FD signal.
- Gaisser-Hillas fit of the reconstructed profile must have $\chi^2/Ndof < 2.5$.
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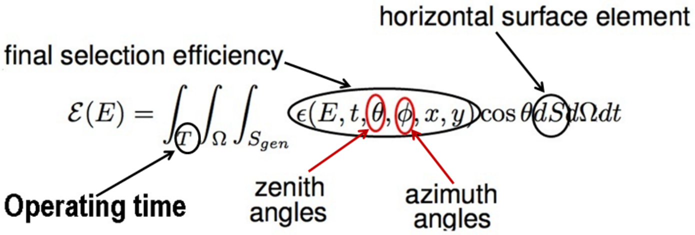
Exposure Calculation

Total Exposure:

$$\mathcal{E}(E) = \int_T \int_\Omega \int_{S_{gen}} \epsilon(E, t, \theta, \phi, x, y) \cos\theta \, dS \, d\Omega \, dt$$



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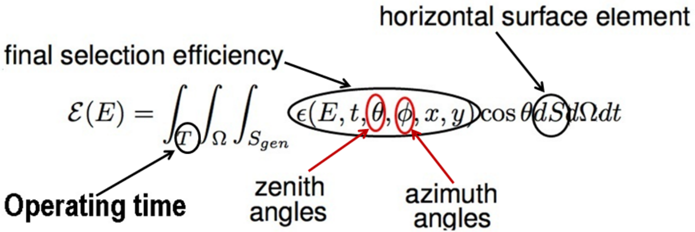

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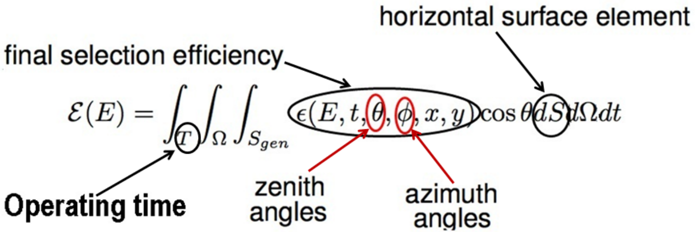

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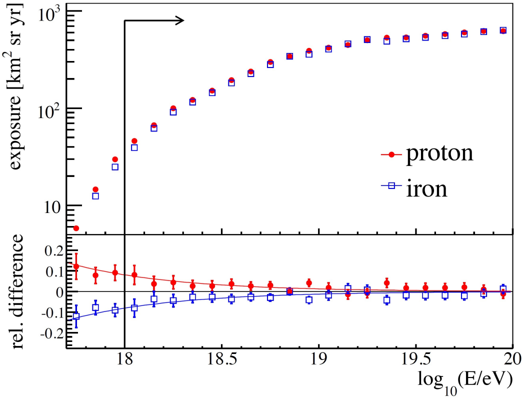
- Syst. Uncertainty for mass composition: 8% at $10^{18}eV$ and 1% at $10^{19}eV$
- 50% p and 50% iron.
- Exposure dependence on the hadronic model is less than 2%



Taken from The Pierre Auger Collaboration, arXiv:1002.1975v1 [astroph.HE] 2010

Exposure calculation

- Syst. Uncertainty for mass composition: 8% at $10^{18}eV$ and 1% at $10^{19}eV$
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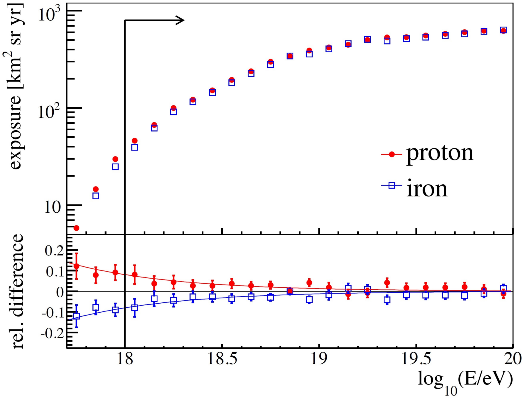

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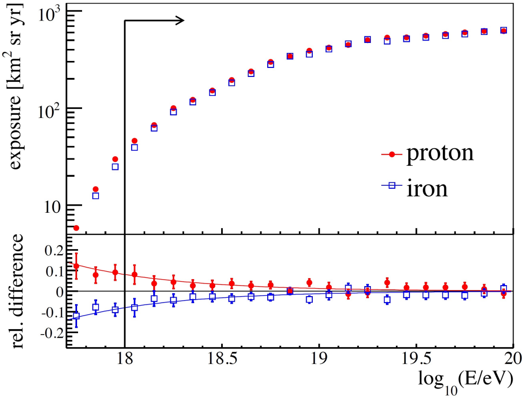


Taken from The Pierre Auger Collaboration, arXiv:1002.1975v1 [astroph.HE] 2010

Flux calculation

Number of detected events passing the quality cuts

Flux of cosmic rays

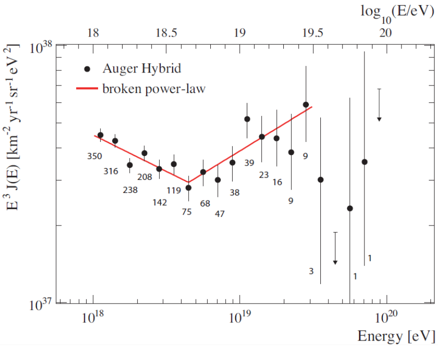
$$J(E) = \frac{d^4 N_{inc}}{dE\,dA\,d\Omega\,dt} \approx \frac{\Delta N_{sel}(E)}{\Delta E} \frac{1}{\mathcal{E}(E)}$$

Number of cosmic rays with incident energy E

Energy dependent-exposure

Approx. is made using the total exposure function $\mathcal{E}$ and $\Delta N_{sel}(E)$ which is the number of selected events.

Hybrid data parameters



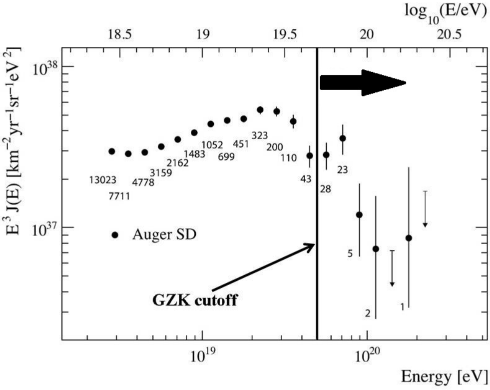
Taken from The Pierre Auger Collaboration, arXiv:1002.1975v1 [astro-ph.HE] 2010

- Ankle

$$log_{10}\frac{E_{ankle}}{eV} = 18.65 \pm 0.09(stat) {}^{+0.10}_{-0.11}(sys)$$

- Power law indices
- $\gamma_1 = 3.28 \pm 0.07(stat) {}^{+0.11}_{-0.10}(sys)$
- $\gamma_2 = 2.65 \pm 0.14(stat) {}^{+0.16}_{-0.14}(sys)$
- Syst uncert $\rightarrow$ effect of the unknown mass composition

Update of the SD spectrum



Taken from The Pierre Auger Collaboration, arXiv: 1002.1975v1

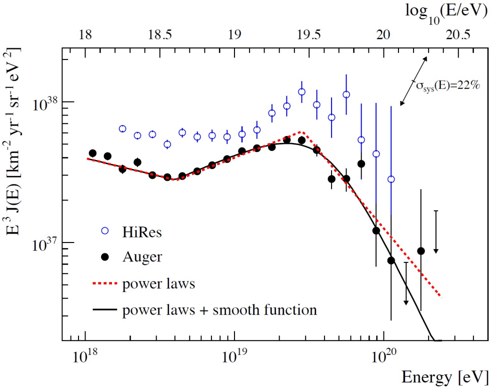
- Data update based on SD data until Dec 2008.
- Current exposure 12790 Km^2sr yr.
- Energy estimator of the SD is corrected for shower attenuation effects using a constant intensity method.

Combined Auger Spectrum

- To combine hybrid and updated SD data, the scale parameter k is used to match the difference between the two sets of data.
- The function at higher energies is given by

$$J(E; E > E_{ankle}) \alpha \frac{E^{-\gamma_2}}{1 + e^{\frac{log_{10}(E) - log_{10} E_{1/2}}{log_{10}(W_e)}}}$$

Combined energy spectrum and fitted parameters and statistical uncertainties.



parameter	power laws	power laws + smooth function
$\gamma_1(E < E_{ankle})$	3.26 ± 0.04	3.26 ± 0.04
$\log_{10}(E_{ankle}/eV)$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E > E_{ankle})$	2.59 ± 0.02	2.55 ± 0.04
$\log_{10}(E_{break}/eV)$	19.46 ± 0.03	
$\gamma_3(E > E_{break})$	4.3 ± 0.2	
$\log_{10}(E_{1/2}/eV)$		19.61 ± 0.03
$\log_{10}(W_c/eV)$		0.16 ± 0.03
χ^2/ndof	38.5/16	29.1/16

Taken from The Pierre Auger Collaboration, arXiv:1002.1975v1 [astro-ph.HE] 2010

Outline

Conclusions

- The CR flux has been measured with the Pierre Auger Observatory by applying two differents techniques.
- Good agreement in the overlapping energy range.
- A combined spectrum has been derived covering energy range $10^{18}eV - 10^{20}eV$.
- $$\gamma = \left\{ \begin{array}{ll} 3.26 \pm 0.04 & \text{below the ankle,} \\ 2.55 \pm 0.04 & \text{above the ankle} \end{array} \right\}$$
- Suppression is similar to what is expected from GZK effect.

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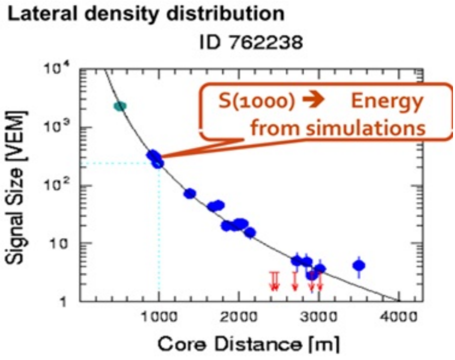
Group E Collaboration - CLASHEP 2013
Thank You

Backup slide

About the Energy estimator:

$$S(r) = S(1000)(\frac{r}{100})]^{-\beta}(\frac{r+700}{1700})^{-\beta}$$



Taken from M. Dova - CLASHEP 2013.

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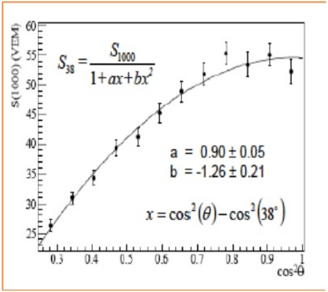
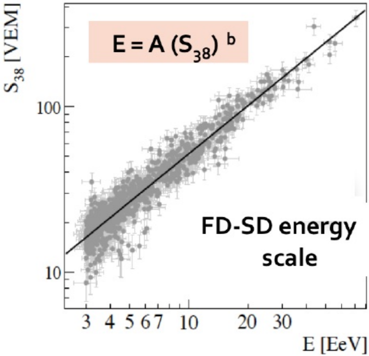


Zenith angle dependence of s1000



Taken from M. Dova - CLASHEP 2013.

Backup slide

- The normalization uncertainties are used as additional constraints in the combination.
- The combination is procedure used the scale parameter k.
- The parameter k, is precisely the difference between the two measurements.
- The equation 2 is another model function which unifies the two higher energy ranges such as that the change in the energy not change abrupt in 2×10^{19}eV.
- The combined energy spectrum if fitted with two functions and compared to data from the HiRes instrument. The systematic uncertainty of the flux scaled by E^3 due to the uncertainty of the energy scale of 22% is indicated by arrows. It has been used three power laws with free breaks between them. A continuation of the power law above the ankle to highest energies can be rejected with more than

Backup slide

- Photon energy threshold in the PRF:

$$E_{\gamma}^{th} = \frac{(m_{p,n,\Delta} + \Sigma m_{\pi})^2 - m_p^2}{2m_p} \quad (1)$$

- Making a lorentz transformation to the CRF where $E_{\gamma} = \epsilon = 2.5.10^{-4} meV$

$$\epsilon = \gamma(E_{\gamma}^{th} - \beta p_{\gamma}^{th}) = \sqrt{\frac{1-\beta}{1+\beta}} E_{\gamma}^{th} \quad (2)$$

- Finding β, the relative velocity between PRF and CRF, the energy of the proton in the CRF can be calculated:

$$E_{CRF}^{th} = m_p \gamma = 1.068.10^{20} eV \quad (3)$$

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The Threshold energy for the other channels is of the same order:

Channel	$E_{\gamma}^{th}(PRF)$	$E_{th}(CRF)$
$p\gamma \rightarrow \pi^+\pi^-\pi^0 p$	$505.51\ MeV$	$3.73 \cdot 10^{20}\ eV$
$p \rightarrow \Delta^{++}\pi^-$	$533.35\ MeV$	$3.94 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \Delta^0\pi^+$	$533.35\ MeV$	$3.94 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \pi^+\pi^- p$	$320.63\ MeV$	$2.37 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \pi^0\pi^0 p$	$308.80\ MeV$	$2.28 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \pi^+\pi^- n$	$321.35\ MeV$	$2.37 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \pi^0\pi^0\pi^0 p$	$492.32\ MeV$	$3.64 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \pi^+\pi^+\pi^- n$	$513.02\ MeV$	$3.79 \cdot 10^{20}\ eV$
$p\gamma \rightarrow \pi^+\pi^0\pi^0 n$	$507.38\ MeV$	$3.75 \cdot 10^{20}\ eV$

Backup slide

- Pair production is responsible for the ankle:

$$p\gamma \rightarrow e^{+}e^{-}p \quad (4)$$

- Photon threshold energy in the PRF:

$$E_{\gamma}^{th}(PRF) = \frac{(m_p + 2m_e)^2 - m_p^2}{2m_p} \quad (5)$$

- Energy of the proton on the CRF:

$$E_{\gamma}^{th}(PRF) = 1.022MeV \longrightarrow E_p(CRF) = 7.54.10^{17}eV \quad (6)$$

Backup slide

Absolute Calibration

- Drum-shaped light source mounted on the FD apertures.
- Provides a pulsed photon flux of known intensty
- All pixels are triggered.
- After calibration some pixels are checked with laser calibration.

Backup slide

- A laser pulse is shot vertically into the air with known intensity from the Central Laser Facility (CLF).
- Nitrogen laser is used (337 nm).
- The response of each pixel to the known (calculated) number of photons performs a calibration for those pixels.
- Overall calibration uncertainty $\approx 12\%$, dominated by atmospheric effects and probe calibration.

Backup slide

- Total background signal is sum of electronics (PMT and electronics noise) and sky brightness (airglow, moonlight, stars and planet light, twilight, artificial light).
- 3-5 ADC counts for electronics
- 20 ADC counts for cloudy nights
- 25-60 ADC counts for clear moonless nights.
- Several hundred ADC counts when moon is present.
- Optimal background: 25-60 ADC counts. Photon background flux of 100-250 photons $m^{-2}\,\mathrm{deg}^{-2}\,\mu s^{-1}$. These events are used for analysis.