The AUGER Experiment

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Summary

- Auger Motivations
- The Auger detectors
- Results and Open Issue
More than fifty years ago Greisen, Zatsepin and Kuzmin concluded that due to the presence of the Cosmic Microwave Background the universe had to be opaque to charge particle of energy larger than $10^{20}$ eV.

In the 90s the two experiments that could explore this region of energy gave inconsistent results.

The main goal of the AUGER experiment was to verify the existence of the GZK cutoff and study the nature of the highest energy cosmic rays.
The Pierre Auger Collaboration

18 Countries
91 Institutions
~ 463 members

Argentina
Australia
Bolivia
Brazil
Croatia
Czech Rep.
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
UK
USA
Vietnam
The Pierre Auger Detector

Hybrid Detector:

Array of 1660 water Cherenkov detectors
  covering 3000 km²
  duty cycle: 100%

Fluorescence telescopes
  27 FDs (30°x30° each)
  duty cycle: 14%

Better geometric reconstruction, cross-calibration, control of systematic.
The Pierre Auger Observatory

1660 tanks installed!

27 FD Telescopes (4 positions)!

Completed in 2008!

Taking data since 2004

≈ 3000 evts/yr with E > 10^{19} eV
The Pierre Auger Observatory

World largest array! 3000 km$^2$ area
The Surface Detector (SD)

- Communication antenna
- GPS antenna
- Electronics enclosure
  40 MHz FADC, local triggers, 10 Watts
- Solar Panel
- Battery box
- Plastic tank with 12 tons of water
- three 9" PMTs (XP1805)
The Fluorescence Detector (FD)
The Fluorescence Detector (FD)

6 telescopes with a FOV of 30° x 30°
The Telescope FD

- Corrector ring (2.2 m)
- UV Filter
- 3.4m mirror
- Camera with a FOV 30°x30°

Duty cycle 14%

UV optical filter (also: protection from outside light, gain a factor 2 in from outside)
Detector Performance: the FD Energy Scale

Detector calibration

Fluorescence yield (from laboratory measurements)

Geometry

\[ \frac{A}{R_i^2} \]

Atmosphere

\[ T(\lambda) \]

Photons in FD FOV

\[ N_\gamma(\lambda) \]

Photons at diaphragm

ADC counts

\[ E_{\text{dep}} \]
The FD Energy Scale

\[ E_{\text{dep}} \rightarrow N_\gamma(\lambda) \rightarrow \text{Photons in FD FOV} \rightarrow \text{Photons at diaphragm} \rightarrow \text{ADC counts} \]

Fluorescence yield

\[ \text{Atmosphere} \quad T(\lambda) \]

Detector calibration
## The FD Energy Scale

### Uncertainties on Previous Energy Scale

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute fluorescence yield</td>
<td>3.4%</td>
</tr>
<tr>
<td>Fluores. spectrum and quenching param.</td>
<td>1.1%</td>
</tr>
<tr>
<td><strong>Sub total (Fluorescence Yield)</strong></td>
<td>3.6%</td>
</tr>
<tr>
<td>Aerosol optical depth</td>
<td>3% ± 6%</td>
</tr>
<tr>
<td>Aerosol phase function</td>
<td>1%</td>
</tr>
<tr>
<td>Wavelength dependence of aerosol scattering</td>
<td>0.5%</td>
</tr>
<tr>
<td>Atmospheric density profile</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Sub total (Atmosphere)</strong></td>
<td>3.4% ± 6.2%</td>
</tr>
<tr>
<td>Absolute FD calibration</td>
<td>9%</td>
</tr>
<tr>
<td>Nightly relative calibration</td>
<td>2%</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>3.5%</td>
</tr>
<tr>
<td><strong>Sub total (FD calibration)</strong></td>
<td>9.9%</td>
</tr>
<tr>
<td>Folding with point spread function</td>
<td>5%</td>
</tr>
<tr>
<td>Multiple scattering model</td>
<td>1%</td>
</tr>
<tr>
<td>Simulation bias</td>
<td>2%</td>
</tr>
<tr>
<td>Constraints in the Gaisser-Hillas fit</td>
<td>3.5% ± 1%</td>
</tr>
<tr>
<td><strong>Sub total (FD profile rec.)</strong></td>
<td>6.5% ± 5.6%</td>
</tr>
<tr>
<td>Invisible energy</td>
<td>3% ± 1.5%</td>
</tr>
<tr>
<td>Statistical error of the SD calib. fit</td>
<td>0.7% ± 1.8%</td>
</tr>
<tr>
<td>Stability of the energy scale</td>
<td>5%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>14%</td>
</tr>
</tbody>
</table>

### Improvement in each sector with the exception of FD cal. (largest contribution) work in progress to reduce it

V. Verzi ICRC 2013
The FD Energy Scale

The review of the process of measurement of energy has changed the scale of energy unevenly.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute fluorescence yield</td>
<td>-8.2%</td>
</tr>
<tr>
<td>New opt. eff.</td>
<td>4.3%</td>
</tr>
<tr>
<td>Calibr. database update</td>
<td>3.5%</td>
</tr>
<tr>
<td>Sub total (FD cal.)</td>
<td>7.8%</td>
</tr>
<tr>
<td>Likelihood fit of dE/dX</td>
<td>2.2%</td>
</tr>
<tr>
<td>Folding with point. spr. func.</td>
<td>9.4%</td>
</tr>
<tr>
<td>Sub total (FD prof. rec.)</td>
<td>11.6%</td>
</tr>
<tr>
<td>Invisible energy</td>
<td>4.4%</td>
</tr>
<tr>
<td>Total</td>
<td>15.6%</td>
</tr>
</tbody>
</table>
The Sd detector is calibrated using “hybrid” data. No comparison with the MC is required!
The UHECR Puzzle

Try to solve the UHECR puzzle

E > 10^{18} eV

UHECR Origin

Top - Down Models

- Isotropy in arrival directions
- Photons
- Features in the spectrum

Bottom - Up Models

- Possible anisotropy in arrival directions
- Almost no photons
- Features in the spectrum

Exotic Mechanisms, New Physics

Astrophysical Acceleration Mechanisms
The UHECR Puzzle

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Astrophysical Acceleration Mechanisms
Photons

FD photons search based on $X_{\text{max}}$ distribution

Deeper showers larger curvature

Slower signal, longer risetime

SD photons search based on signal structure
Photons

Exotic Mechanisms
✓ Decay of topological defects
✓ Relic monopoles
✓ Etc.

New Physics
✓ Supersymmetric particles
✓ Strongly interacting neutrinos
✓ Decay of massive new long lived particles
✓ Etc.

GZK region within reach in the next years
Top-down models severely constrained
Favor astrophysical origin of UHECR
Photons: implications

The photon upper limits could exclude the Top-Down scenario

Top - Down Models

Bottom - Up Models

Where and how UHECR are produced?

Compact Object

Extended Object

Transient Phenomena

Stable Emission

Fermi Acceleration

Other Process

Interaction Models

Galactic Origin

Transition from Galactic to Extra

Extragalactic Origin

Stable Emission
The UHECR Puzzle

Bottom - Up Models

- Spectrum Features
- Mass Composition
- Anisotropy

Interaction Models
The Spectrum

SD 1500 m, $\theta < 60^\circ$
- Vertical events
  - Fully efficient: $E \geq 3$ EeV
  - Energy estimator: $S_{38}$

SD 750 m, $\theta < 55^\circ$
- 750 m events
  - Fully efficient: $E \geq 0.3$ EeV
  - Energy estimator: $S_{35}$

SD 1500 m, $62^\circ < \theta < 80^\circ$
- Inclined events
  - Fully efficient: $E \geq 4$ EeV
  - Energy estimator: $N_{19}$

Hybrid (FD + 1 SD), $\theta < 60^\circ$
- Hybrid events
  - Fully efficient: $E \geq 1$ EeV
  - Energy meas.: $E_{FD}$
The Spectrum

Perfect agreement between the different samples.

Exposures at 10 EeV:

- SD vertical: $31645 \pm 950$
- SD inclined: $8027 \pm 240$
- Hybrid: $1496 \pm 25$
- SD 750 m: $79 \pm 4$

A. Schulz ICRC 2013
The Spectrum

Combined spectrum. It is unquestioned the presence of an “ankle” and of a cut-off

The visible cut-off is due to the GZK effect?

Where and how the UHECR are accelerated?

The most natural explanation. A stream of pure protons can reproduce the measured spectrum by Auger. The ankle is a natural consequence of the process of interaction P-γ.
Mass Composition

The main instrument of analysis is the Fluorescence Detector, but also the Surface Array can be used.

\[ (E, \text{Int. Mod.}) \]
\[ X_{\text{max}} \text{ and its RMS sensitive to mass composition} \]

The \( X_{\text{max}} \) position is related to the primary mass.
The fluctuation of the first interaction point are related to the primary mass.

\(<X_{\text{max}}\>\) and its RMS sensitive to mass composition
Key observables for composition studies
Mass Composition

\[ \langle X_{\text{max}} \rangle \text{ became lower with energy} \]

\[ X_{\text{max}} \text{ distributions become narrower with energy} \]

Increase of the mean mass with the energy? Inadequate interaction models?
What is it happening? What is the origin of the cut-off and of the ankle?
Anisotropy

Events with energy larger than 54.8 EeV. Selection angle 3.1°. Reference catalog VCV.

Results not compatible with an isotropic flux.

How we can explain? Few near sources plus an isotropic flux? Similar results obtained by TA.

Deflection P <3°; Deflection Fe 15°-20°

Fraction of correlating events after period I

Green crosses are bins of 19 events
How we can explain this results

- UHECR Rigidity dependent composition of Extragalactic origin
- GZK effect not needed
- Transition from galactic to extragalactic at lower energy (2nd knee)

- UHECR Mixed composition at the sources (Extragalactic origin)
- GZK effect but for Heavy Elements
- Ankle due to transition between Galactic and Extragalactic spectrum.
SD Mass Composition

FD has limited statistic. It "sees" only the e.m. component of the shower.

SD has not been optimized to make mass composition studies, but has the possibility to estimate (with large uncertainty) the number of muons. Muons provide information on the mass of the primary. Combined with FD can put constraints on the interaction models.
Different methodologies developed.

Inclined events $\theta > 60^\circ$

From FADC traces @ 10 EeV

Measurements and Monte Carlo expectations not in agreement. Other types of measures have also contradictions more pronounced.
SD Mass Composition

Different methodologies developed.

Inclined events $\theta > 60^\circ$

Measure the e.m. and muonic components!

Measurements and Monte Carlo expectations not in agreement. Other types of measures have also contradictions more pronounced.
**AUGER: A Summary**

![Graph showing energy distribution with change of slope and cut-off points.](image)

- **Change of the slope.**
  - Light composition.
  - Weak or none anisotropy (no galactic protons).

- **Cut off**
  - The composition became heavy.
  - No galactic neutrons.

- **Anisotropy present but weak.**
  - Not only GZK protons.

**Muons:** Problems with the interaction models? New physics?

Direct measurement of muons and mass composition up to $10^{20}$ eV needed.

**Challenging (open) science case at the highest energy**
The End

Backup
The Spectrum

\[ J(A \times E^{2.67})^{-1} \]

\[ \log_{10}(E/eV) \]

- Red dots: Auger 2013 preliminary
- Blue squares: Auger (ICRC 2011)

\[ \sigma/E (2013) \]
Correction & Systematics

(1) Based on TA-FY model = Kakimoto modified + FLASH

Measured FY/TA-FY = 1.18 ± 0.01(stat) ± 0.18(syst)

TA-FY = 16.4 ph/MeV@300-420nm,1013hPa,293K
4.29ph/MeV@337nm,1013hPa,293K
TA-FY has ~10% systematic uncertainty

(2) Based on Common Model FY 2012 (Absolute Yield is AirFly)

Measured FY/CM-FY2012 = 0.96 ± 0.01(stat) ± 0.15(syst)

337nm FY of CM-FY2012 = 5.61 ph/MeV@1013 hPa,293K
CM-FY2012 has ~4% systematic uncertainty

<table>
<thead>
<tr>
<th>Total Correction</th>
<th>Systematic Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3 %</td>
<td>= 15 %(*)</td>
</tr>
<tr>
<td>- Correction of Beam charge/pulse which measured by Faraday Cup</td>
<td>Fluorescence Detector</td>
</tr>
<tr>
<td>- Contribution of background photons from the ELS container</td>
<td>ELS</td>
</tr>
<tr>
<td>- Contribution of Cerenkov photons</td>
<td>Charge measurement</td>
</tr>
<tr>
<td></td>
<td>Shower geometry and Telescope optics</td>
</tr>
</tbody>
</table>

(*)15% of DATA/MC value before correction

33rd ICRC, July 2-9, 2013, Rio de Janeiro-Brazil
## FD vs SD

<table>
<thead>
<tr>
<th></th>
<th>SD-only</th>
<th>FD-only</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty-cycle</td>
<td>~100%</td>
<td>~10%</td>
<td>~10%</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>1-2 deg</td>
<td>3-5 deg</td>
<td>0.2 deg</td>
</tr>
<tr>
<td>Energy</td>
<td>C &amp; M depend</td>
<td>independent</td>
<td>independent</td>
</tr>
<tr>
<td>Aperture</td>
<td>independent</td>
<td>E, C, M depend</td>
<td>independent</td>
</tr>
<tr>
<td>Energy Thr.</td>
<td>$\sim10^{18.5}$ eV</td>
<td>$\sim10^{17.5}$ eV</td>
<td>$\sim10^{18}$ eV</td>
</tr>
</tbody>
</table>

$E =$ Energy, $M =$ Interaction Model, $C =$ Composition
Above 1 EeV anisotropies could be imprinted in the distribution of arrival directions as the result of the escape of UHECRs from the Galaxy up to the ankle energy.

If UHECRs have already a predominant extragalactic origin their angular distribution is expected to be isotropic to a high level.

Model prediction for an uniform distribution of sources in the galaxy and different compositions
Mass Composition
Anisotropy

Full-Sky Map >10 EeV
(30° smoothing)

$N_{TA} \sim 1800$
($\sim 5200 \ \text{km}^2 \text{sr yr}$)

$N_{Auger} \sim 10900$
($\sim 32000 \ \text{km}^2 \text{sr yr}$)

In the overlap:
$N_{TA} \sim 650$
$N_{Auger} \sim 3400$

PRELIMINARY
Anisotropy: Neutrons

**AUGER has sensitivity to galactic neutron sources**

- Neutrons are undeflected by galactic magnetic fields!
- Flux of neutrons from discrete source would cause an excess of CR events in the direction of the source!
- 1 EeV neutron emitted by Galactic center could be seen!
- Flux of gammas rays from some sources in the galaxy, could be associated to neutron fluxes detectable by Auger!
- Select SD events with $\theta \leq 60^\circ$, good event reconstruction!
- Exposure of 24,880 km$^2$ sr yr, with 429,138 events with energy $\geq 1$ EeV!

No excess found
Mass Composition

We now have a testable hypothesis: TA claims it sees a light composition as energy increases, Auger claims to see composition increasing in mass as energy increases. TA can reconstruct pure proton, helium, nitrogen, etc. and test, including all detector resolution effects and biases, does TA see what Auger sees?

Total bias TA sees in reconstructing pure protons is 12 g/cm². (Note this bias is calculated against unbiased thrown proton distribution).

TA reconstructed $<X_{\text{max}}>$ for the Auger composition mix does not look like TA reconstructed $<X_{\text{max}}>$ for pure protons.

William F. Hanlon, 33rd ICRC, Rio de Janeiro, Brazil, 6 July 2013