Recent results from the Pierre Auger Observatory

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http://www.auger.org/archive/authors_2016_04.html
UHECR: key problems of astrophysics & fundamental physics

Cosmic particle accelerators
UHECR energy spectrum, mass composition, arrival directions

Particle interactions at the energies inaccessible in laboratory
Validity of interaction models at the extreme CR energies
PAO hybrid design for CR detection above $10^{17}$ eV

- conceived in 1990s
- Engineering Array: 2000-2003
- start operation: 2004
- Completed: 2008
- Upgrade “AugerPrime”: 2016-2018
- Planned operations ≥ till 2025
  + radio antennas, muon detectors
  + atmospheric monitoring, ....

[longitudinal profile]

[lateral distribution]
The Pierre Auger Collaboration

About 450 people from 16 countries and 68 institutions
The Pierre Auger Observatory

Surface detector (SD)  
duty cycle 100%

SD-1500 m  
3000 km² area  
1600 water-Cherenkov detectors (WCDs)

SD-750 m  
23.5 km² area  
61 WCDs

Fluorescence detector (FD)  
duty cycle 15%

5 units at 4 locations  
4 units × 6 fluorescence telescopes overlooking SD-1500 m array  
FOV 30° × 30° in azimuth and elevation  
minimum elevation of 1.5°  
1 unit × 3 fluorescence telescopes (HEAT) overlooking SD-750 m array  
FOV [30°, 60°] in elevation

The Pierre Auger Observatory

FD Los Leones

HEAT telescopes

neighbor WCD
Primary CR reconstruction

**FD energy:** integral of the longitudinal profile

**FD:** position \( X_{\text{max}} \) of the shower maximum => information on the primary mass

**SD energy:** \( \propto \) signal \( S(1000) \) at 1 km from the shower core

**SD:** shower geometry (core position and arrival direction)
Auger events

SD-1500 m, $\theta < 60^\circ$

Vertical events
- fully efficient:
  - $E > 3 \text{ EeV}$
- energy estimator: S38

SD-750 m, $\theta < 55^\circ$

“Infill” events
- fully efficient:
  - $E > 0.3 \text{ EeV}$
- energy estimator: S35

SD-1500 m, $60^\circ < \theta < 80^\circ$

Inclined events
- fully efficient:
  - $E > 4 \text{ EeV}$
- energy estimator: N19

Hybrid (FD + $\geq 1$ SD), $\theta < 60^\circ$

Hybrid events
- fully efficient:
  - $E > 1 \text{ EeV}$
  - energy measured

Combined measurement allows to cover 3 decades in energy
Auger energy calibration & systematics

FD: the common energy scale
free of SD-related uncertainties (cascade simulation + hadronic interaction models)

Energy systematic uncertainties:
FD calibration: 9.9%
FD profile reconstruction 6.5-5.6%
Atmospheric conditions: 3-6%
Stability of the energy scale 5%
Fluorescence yield: 3.6%
Invisible energy 3-1.5%
Statistical error of SD calibration fit 0.7-1.8%

FD energy scale: 14%

SD resolutions for energy reconstruction:
S(1000): 22% (@3 EeV) to 12% (highest E)
Energy: 16% (@3 EeV) to 12% (highest E)

Hybrids (FD + at least 1 SD station):
Energy resolution 8%
Energy spectra from SD and hybrid data

![Graph showing energy spectra with data points for different SD configurations and a hybrid setup.](image)

<table>
<thead>
<tr>
<th></th>
<th>SD-1500 m</th>
<th>SD-750 m</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure [km² sr yr]</td>
<td>42500±1300</td>
<td>10900±300</td>
<td>150±5</td>
</tr>
<tr>
<td>Number of events</td>
<td>102901</td>
<td>15614</td>
<td>61130</td>
</tr>
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Auger all-particle CR spectrum

Combined maximum-likelihood fit, the normalisations of the different spectra are allowed to vary within the corresponding uncertainties

$\gamma_1 = 3.29 \pm 0.02 \pm 0.05$

$\gamma_2 = 2.60 \pm 0.02 \pm 0.1$

Ankle at $4.82 \pm 0.07 \pm 0.8$ EeV

Flux falling to 1/2 of the 2$^{nd}$ power law extrapolation at $42.1 \pm 1.7 \pm 7.6$ EeV

$\Delta \gamma \approx 3.14$
Update on $X_{\text{max}}$ measurements

robust mass-sensitive EAS observable

uncertainties due to models $\ll$ difference proton-iron

Extending analysis down to 0.1 EeV using HEAT

hybrid events used

$X_{\text{max}}$ resolution $< 30$ (20) g/cm$^2$ above 0.1 (0.63) EeV

A. Porcelli for the Auger Coll. PoS (ICRC2015) 420
First two moments of $X_{\max}$ distributions

Below $\approx 2$ EeV, $<X_{\max}>$ increases by $\approx 85 \text{ g cm}^{-2}$ per energy decade.

Above this energy, $<X_{\max}>$ decreases by $\approx 26 \text{ g cm}^{-2}$ per energy decade.

$\Rightarrow$ the composition is getting lighter (heavier) below (above) $\approx$ half of the ankle energy.
Elemental primary CR fractions from $X_{\text{max}}$ fits

Three hadronic models used to fit the data with 2, 3 or 4 (p, He, N, Fe) elemental groups

Iron fraction is almost absent, fractions of p and He change strongly with energy

Proton fraction present at 30 EeV ?!
Composition at the ankle: a joint $X_{\text{max}}^*$ & $S^*(1000)$ analysis

lighter nuclei produce deeper showers with smaller signal (less muons) $\Rightarrow S^*(1000)$

general air shower properties, minor model dependence  

P. Younk, M. Risse, APh 35 (2012) 807

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correlation in the data with $\lg(E/\text{eV}) = 18.5-19.0$ compared with simulated primary beams

Correlation coefficient $r_G (X_{\text{max}}^*, S^*(1000)) \geq 0$ for pure beams, EPOS-LHC: 0 (p), $+0.08$ (Fe)

$r_G (X_{\text{max}}^*, S^*(1000))$ minimal (negative) for the $0.5$ p $- 0.5$ Fe mixture (-0.37 for EPOS-LHC)

In data, $r_G = -0.125 \pm 0.024$ $\Rightarrow$ primary CR composition near the ankle is mixed
Dispersion of primary CR masses in data

Conversion of $X_{\text{max}}$ moments to $\ln A$ moments applied

Data near the ankle are consistent with $1.0 \leq \sigma(\ln A) \leq 1.7$ for the three models.

Results are robust against modifications of hadronic models.

“Dip” model of the ankle is disfavoured.

A. Yushkov for the Auger Coll. PoS (ICRC2015) 335
Combined fit of spectrum and composition data

Identical uniformly distributed sources with a rigidity-dependent injection of nuclei

Several CR propagation models cross sections for photo-disintegration and for EBL spectrum

LHC-tuned models for air-shower particle interactions the atmosphere

Best fit: flux limited by max. energy @ sources

Hard injection spectral index $\gamma \sim 1$ preferred, with low cutoff energy $E \sim Z \times 4.7$ EeV

Second scenario $\gamma \sim 2$, $R \sim 70$ EV disfavored ($\sim 7.5\sigma$): wider mass dispersion than in the data
**Auger neutrino and photon limits**

Cosmogenic (“GZK”) photon and neutrino emission, flux depends on CR mass distribution

Difference in air shower development w.r.t. nuclei => difference in WCD signal time structure

10-year Auger SD data set analysed, 0 neutrino candidates & 4 photon candidates found

Upper limits on photon and neutrino fluxed derived, assuming differential flux \( dN(E) = k \cdot E^{-2} \)

Photon limits: top-down models clearly disfavored, *astrophysical UHECR scenarios preferred*

Both limits reach predictions for cases of a pure proton composition at the UHECR sources

*see today's talk on neutrino analyses by Lili Yang*
Arrival directions of the highest energy Auger events

UHECR sources within GZK sphere => anisotropy at small or intermediate angular scales?

602 events above 40 EeV collected in 10 years, -90° to +45° in declination (< 80° in zenith angle)

Search in circles 1-30°, $E_{\text{thresh}}$ up to 80 EeV for

1) intrinsic anisotropies 2) correlations with astrophysical structures (e.g. GP, SGP, GC) and plausible UHECR candidates: Cen A; catalogs: galaxies, X-ray emitting AGN, jetted radiogalaxies: +scan distance & luminosity

No significant anisotropy found. Two largest excesses are above 58 EeV (post-trial $p \approx 1.4\%$):

a) UHECR within 18° of Swift-BAT AGNs closer than 130 Mpc and brighter than $10^{44}$ erg/s
b) UHECR within 15° of Cen A (consistent with the largest overdensity found, see the right plot)

Large number of low luminosity sources or large-Z nuclei? CR mass information is crucial!
Large scale anisotropy at the highest energies?

May be indicative of the collective CR motion and/or of the CR sources distribution

Rayleigh analysis in right ascension and azimuth

Dipole amplitude at $E > 8$ EeV

Auger $(7.3 \pm 1.5)\% \ (p=6.4 \times 10^{-5})$

Auger and TA $(6.5 \pm 1.9)\% \ (p=5 \times 10^{-3})$

Dipole directions are compatible between 2 analyses

Phase changes from $\approx 270^\circ \ (< 1$ EeV) to $\approx 100^\circ \ (> 8$ EeV)

Transition from galactic to extragalactic CR ?

Prescription running for Auger to set confidence level
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Particle interactions at the energies inaccessible in laboratory
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Conversion of $X_{\text{max}}$ moments to $\ln A$ moments

One-to-one relation between $X_{\text{max}}$ and $\ln A$ moments

$$\langle X_{\text{max}} \rangle \approx \langle X_{\text{max}}^p \rangle - D_p \langle \ln A \rangle$$

$$\sigma^2(X_{\text{max}}) \approx \langle \sigma_{\text{sh}}^2 \rangle + D_p^2 \sigma^2(\ln A)$$

$\langle \sigma_{\text{sh}}^2 \rangle$ — shower-to-shower fluctuations for $\langle \ln A \rangle$;

$D_p = d\langle X_{\text{max}}^p \rangle / d\ln E$ (elongation rate for protons).

$$\langle \ln A \rangle = \sum_i f_i \ln A_i, \quad (f_i — \text{relative fractions of masses } A_i = 1, \ldots, 56)$$

$$\langle \ln A \rangle(\text{proton}) \approx 0; \quad \langle \ln A \rangle(\text{Fe}) \approx 4$$

Purity of the primary beam

$$\sigma^2(\ln A) = \langle \ln^2 A \rangle - \langle \ln A \rangle^2$$

For pure beams $\sigma^2(\ln A) = 0$; maximal mixing $0.5p - 0.5\text{Fe} \quad \sigma^2(\ln A) \approx 4$
transition from lighter to heavier composition above 2 EeV

dispersion of masses decreases with energy

QGSJetII-04: $\sigma^2(\ln A) < 0$ (within 2$\sigma$), too large shower-to-shower fluctuations?
Muons in highly inclined events

Muon density profiles in highly inclined events:
- depend strongly on azimuth (geomagnetic deflection) and zenith (atmospheric absorption)
- depend weakly on energy, mass, model for showers with $\theta > 60^\circ$

=> factorization is possible using ratio N19 of measured/reference density:

$$\rho_\mu(\vec{r}) = N_{19}\rho_{\mu,19}(\vec{r}; \theta, \phi)$$

Muon content $R_\mu$ is the ratio data/MC:

$$R_\mu = \frac{N_{19}^{\text{data}}}{N_{19}^{\text{MC}}}$$

Reference density profile $\rho_{\mu,19}$ [hits/station]

MC: proton, QGSJet II-03
$E = 10^{19}$ eV
$\theta = 80^\circ$
$\phi = 0^\circ$

$R_\mu$ calibration for hybrid events

Fit: $\langle R_\mu \rangle = a(E/10^{19}$ eV)$^b$

174 Auger hybrid events

Auger Coll., PRD 91 (2015) 032003
Average muon content

Data 01/2004 – 12/2012

Zenith angles [62°; 80°]

Low EM contamination

E > 4 EeV

SD array fully efficient

174 events after selection

Systematic uncertainty 18%

\(<R_\mu^{\text{data}}\) is larger than MC values for iron, in conflict with \(<\ln A\) from \(X_{\text{max}}\)

\(d<\ln R_\mu^{\text{data}}>/d \ln E\) deviates from pure proton (iron) by 2.2σ (2.6σ),

and is positive in agreement with the \(<X_{\text{max}}\) evolution (transition from lighter to heavier elements)
Average log muon content

Muon content in MC (for \(\langle \ln A \rangle\) from \(X_{\text{max}}\)) is (30 – 80)% smaller than in data, minimal difference is 1.4 \(\sigma_{\text{(sys)}}\) with EPOS-LHC
Summary

Spectrum
Combined measurements over 3 decades in E, ankle observed at about 5 EeV, flux suppression above 40 EeV

Composition
Gets heavier (lighter) with increasing energy in the region above (below) ~ 2 EeV, half the ankle energy

Spectrum and composition together favor the “source extinction” scenario

Photons & Neutrinos
Photon limits above 1 EeV strongly disfavor top-down models. Absence of GZK neutrinos disfavors pure proton composition

Arrival directions
Compatible with isotropy at small and intermediate scales. Hints on a dipole anisotropy above 10 EeV

Hadronic interactions
Great potential of mass-sensitive observables. Muon content is larger in data w.r.t. simulations (by a model-dependent factor)

Open science case at the highest energies
- lack of composition data in the suppression region
- need to better understand hadronic interaction models
- need to separate a light component to identify UHECR sources
Perspectives: detector upgrade “AugerPrime”

Goal: improve on the sensitivity to mass composition in the suppression region

Equip each WSD with scintillator layer on top => Scintillators sensitive to the electromagnetic content of the shower => muon component estimate

In addition:
- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

Timeline:
- July 2016: Engineering Array, 12 stations equipped with scintillators
- End of 2016: evaluation
- 2017-2018: deployment of 1600 SSD
- Until 2025: data-taking

4 m² scintillators, 1 cm thick
AugerPrime: discrimination of scenarios

Scenario 1: maximum rigidity model

Scenario 2: photo-disintegration model

AugerPrime: discrimination of scenarios

Reference: maximum rigidity model

- Standard scenario 1 (almost no protons)
- Scenario 1 with 10% protons added

Significance of distinguishing scenarios with and without 10% protons

(ideal case for knowing proton predictions without uncertainty due to had. int. models)