Latest results from the Pierre Auger Observatory
(cosmic rays, the Auger detectors, observations)

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(On behalf of the Pierre Auger Collaboration)

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Cosmic Rays flux as a function of energy
Cosmic Rays flux as a function of energy

Fluxes of Cosmic Rays

- Knee (1 particle per m²-year)
- LHC ($\sqrt{s_{pp}}$) (1 particle per m²-year)
- Ankle (1 particle per km²-year)

Flux (m³ s⁻¹ GeV⁻¹)

Energy (eV)
There is not clear explanation for cosmic rays with energies above $10^{20}$ eV.
Protons with energies above $6 \times 10^{19}$ eV interact with the microwave background radiation (CMB) and they rapidly lose energy (GZK cutoff)
The Pierre Auger Collaboration

Argentina  
Australia  
Brasil  
Colombia*  
Czech Republic  
France  
Germany  
Italy  
Mexico  
Netherlands  
Poland  
Portugal  
Romania  
Slovenia  
Spain  
USA  

*associated

Pierre Auger Observatory

Full members  
Associate members
“The Pierre Auger Observatory...employing a giant array of particle counters and an optical fluorescence detector...is a “hybrid” ground detector...”
The Pierre Auger Observatory, Argentina

SD station (1500 stations)

FD (4 sites + HEAT)

Laser station (CLF)

For monitoring: atmosphere, timing, FD alignment, and reconstruction performance
The Pierre Auger Observatory, Argentina
The Fluorescence Detector
Los Leones
The Fluorescence Detector
The total energy is obtained by integrating the energy deposit profile. The average statistical uncertainty is 12%.
The energy converter:

Compare ground parameter $S(1000)$ with the fluorescence detector energy.

The **systematic uncertainties** of the fluorescence detector (14%) are transferred to the surface detector.

The surface detector **energy resolution** is about 20% at the lowest energies and 10% at the highest energies.

**Note:** $S_{1000}$ for a given shower energy varies depending on the zenith angle. So, $S_{38}$ is the corresponding expectation for a 38° shower, given the $S_{1000}$ measurement.
The Cosmic Ray Energy Spectrum

Four independent measurements
The Cosmic Ray Energy Spectrum
(combining all measurements)

Fitted function:

\[ J(E) = J_0 \left( \frac{E}{E_{\text{ankle}}} \right)^{-\gamma_1} \quad \text{for } E < E_{\text{ankle}} \]
\[ J(E) = J_0 \left( \frac{E}{E_{\text{ankle}}} \right)^{-\gamma_2} \left[ 1 + \left( \frac{E_{\text{ankle}}}{E_{s}} \right)^{\Delta \gamma} \right]^{-1} \left[ 1 + \left( \frac{E}{E_{s}} \right)^{\Delta \gamma} \right]^{-1} \quad \text{for } E > E_{\text{ankle}} \]

Fitted parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J_0 )</td>
<td>( 3.30 \pm 0.15 \pm 0.20 \times 10^{-19} )</td>
<td>( \text{eV}^{-1}\text{km}^{-2}\text{sr}^{-1}\text{yr}^{-1} )</td>
</tr>
<tr>
<td>( E_{\text{ankle}} )</td>
<td>( 4.82 \pm 0.07 \pm 0.8 )</td>
<td>( \text{GeV} )</td>
</tr>
<tr>
<td>( E_s )</td>
<td>( 42.09 \pm 1.7 \pm 7.61 )</td>
<td>( \text{GeV} )</td>
</tr>
<tr>
<td>( \gamma_1 )</td>
<td>( 3.29 \pm 0.02 \pm 0.05 )</td>
<td></td>
</tr>
<tr>
<td>( \gamma_2 )</td>
<td>( 2.60 \pm 0.02 \pm 0.1 )</td>
<td></td>
</tr>
<tr>
<td>( \Delta \gamma )</td>
<td>( 3.14 \pm 0.2 \pm 0.4 )</td>
<td></td>
</tr>
</tbody>
</table>
## Arrival Directions

### Cross correlation studies

<table>
<thead>
<tr>
<th>Objects</th>
<th>$E_{\text{th}}$</th>
<th>$\Psi$</th>
<th>$D$</th>
<th>$\mathcal{L}_{\text{min}}$</th>
<th>$f_{\text{min}}$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MRS Galaxies</td>
<td>52</td>
<td>9</td>
<td>90</td>
<td>-</td>
<td>$1.5 \times 10^{-3}$</td>
<td>24%</td>
</tr>
<tr>
<td>Swift AGNs</td>
<td>58</td>
<td>1</td>
<td>80</td>
<td>-</td>
<td>$6 \times 10^{-5}$</td>
<td>6%</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>72</td>
<td>4.75</td>
<td>90</td>
<td>-</td>
<td>$2 \times 10^{-4}$</td>
<td>8%</td>
</tr>
<tr>
<td><strong>Swift AGNs</strong></td>
<td>58</td>
<td>18</td>
<td>130</td>
<td>$10^{44}$</td>
<td>$2 \times 10^{-6}$</td>
<td>1.3%</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>72</td>
<td>4.75</td>
<td>90</td>
<td>$10^{39.33}$</td>
<td>$5.1 \times 10^{-5}$</td>
<td>11%</td>
</tr>
<tr>
<td><strong>Centaurus A</strong></td>
<td>58</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>$2 \times 10^{-4}$</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

*Table 1:* Summary of the parameters of the minima found in the cross-correlation analyses.
Arrival Directions  Large Scale Anisotropy

Harmonic analysis in right ascension
85% sky coverage

Sky map of the CR flux (45° smoothing)

4 EeV < E < 8 EeV

E > 8 EeV

Dipole amplitude: 7.3 +- 1.5%  (p=6.4x10^{-5})
Pointing to (a,d) = (95° +- 13°, 39° +- 13°)

Arrival Directions  Large Scale Anisotropy

DIPOLE PHASE

DIPOLE AMPLITUDE

[Graphs showing phase and amplitude variations with energy]
Evolution of an Air Shower

An air shower has three main components:

a) the **electromagnetic**
b) the **muonic**, and
c) the **hadronic**.
Auger measurements related to mass composition

Correlation factor between:

$X_{\text{max}}$ and $S_{1000}$

(Hybrid events)
Depth of maximum of air-shower profiles at the Pierre Auger Observatory. I. Measurements at energies above $10^{17.8}$ eV
$X_{\text{max}}$ moments combining HEAT and standard FD measurements

**Average of $X_{\text{max}}$**

**Std. Deviation of $X_{\text{max}}$**

Standard FD  →  PHYSICAL REVIEW D 90, 122005 (2014)
\( \langle \ln A \rangle \) and dispersion of \( \ln A \) estimated from the \( X_{\text{max}} \) moments

**EPOS-LHC (Mean of \( \ln A \))**

**EPOS-LHC (Variance of \( \ln A \))**
\( \langle \ln A \rangle \) and dispersion of \( \ln A \) estimated from the \( X_{\text{max}} \) moments.

**QGSJetII-04 (Mean of \( \ln A \))**

**QGSJetII-04 (Variance of \( \ln A \))**

\( \log_{10}(E/\text{eV}) \) vs \( \langle \ln A \rangle \) and \( \sigma^2(\ln A) \).
Xmax distribution fits

PHYSICAL REVIEW D 90, 122006 (2014)
Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events

FIG. 4 (color online). Average muon content \( \langle R_\mu \rangle \) per shower energy \( E \) as a function of the shower energy \( E \) in double logarithmic scale. Our data is shown bin by bin (circles) together with the fit discussed in the previous section (line). Square brackets indicate the systematic uncertainty of the measurement; the diagonal offsets represent the correlated effect of systematic shifts in the energy scale. The grey band indicates the statistical uncertainty of the fitted line. Shown for comparison are theoretical curves for proton and iron showers simulated at \( \theta = 67^\circ \) (dotted and dashed lines). Black triangles at the bottom show the energy bin edges. The binning was adjusted by an algorithm to obtain equal numbers of events per bin.
$X_{\mu \text{ max}}$

Muons in air showers at the Pierre Auger Observatory: Measurement of atmospheric production depth

**FIG. 8** (color online). $\langle X_{\text{max}}^{\mu} \rangle$ as a function of energy. The predictions of different hadronic models for protons and iron are shown. Numbers indicate the number of events in each energy bin, and brackets represent the systematic uncertainty.
Inconsistency in the $\langle \ln A \rangle$ estimates points out deficiencies of the hadronic interaction models. Hadronic models have not been tested experimentally at these high energies.
Correlation factor between:

\[ X_{\text{max}} \quad \text{and} \quad S_{1000} \]

For pure compositions
Correlation factor \( \approx 0 \)

For mixed compositions
Correlation factor \( \neq 0 \)

FD: depth of shower maximum, \( X_{\text{max}} \), scaled to 10 EeV
SD: signal at 1000 m from the core, \( S_{1000} \), scaled to 10 EeV and 38°.

The scaled observables are used, they are marked with an asterisk.
Data

Hybrid (FD and SD)

- 8 years 12/2004 – 12/2012
- $\log(E/eV) = 18.5 - 19.0$
- zenith angles 0° – 65°
- 1376 high-quality events
correlation is significantly negative

Data not consistent with pure composition

$r_G(X_{\text{max}}, S^*(1000))$ for protons

Epos-LHC   QGSJetII-04   Sibyll 2.1
0.00   +0.08   +0.07

difference to data

$\approx 5\sigma$   $\approx 8\sigma$   $\approx 7.5\sigma$

difference is larger for other pure beams

systematics plays only a minor role $\sigma_{\text{syst}}(r_G) \lesssim 0.01$

due to invariance of $r_G$ to additive and multiplicative scale transformations
$r_A = -0.125 \pm 0.024$

$\log_{10}(E/eV) = 18.5 - 19.0$

Auger 2015, preliminary
$r_G = -0.125 \pm 0.024$

$\log(E/eV) = 18.5 - 19.0$

Auger 2015, preliminary

QGSJetII-04 (Variance of $\ln A$)
Interpretation of mass dispersion from \( S_{1000}, X_{\text{max}} \) correlation is consistent with all models.
Sensitivity to neutrinos in Auger

1) Regular proton shower
2) Deep Down-going $\nu$ shower
3) Up-going Earth-skimming $\nu_{\tau}$ shower
4) Down-going $\nu_{\tau}$ interacting in the mountains

Pulse shape and Risetime definition

Area over Peak

- Training data
- Search data
- Monte Carlo $\nu_{\tau}$

$<\text{AoP}> > 1.83$

$\nu_{\tau}$ candidate region
Flux upper limits for Neutrinos and Photons

**Figure 6:** Upper limits to the diffuse flux of UHE neutrinos at 90% C.L. in integrated (horizontal lines) and differential form. Limits described in this work (red lines) are compared with cosmogenic neutrino models [16, 17, 18], the Waxman-Bahcall bound [19], and limits from IceCube [20] and ANITA [21]. All neutrino limits and fluxes are converted to single-flavour.

**Figure 7:** Upper limits at 95% C.L. to the diffuse flux of UHE photons derived in this work (black) shown together with previous results from the Pierre Auger Observatory with hybrid (Hyb) and SD data [22], Telescope Array (TA) [23], Yakutsk (Y) [24], Haverah Park (HP) [25], AGASA (A) [26] and predictions from several top-down [27, 28] and cosmogenic photon models [27, 17].
Magnetic Monopoles

Simulations

Reconstruction of monopole

protons

monopoles

(b) $X_{\text{max}} > X_{\text{up}}$ selection

(b) $\gamma = 10^{11}$

PHYSICAL REVIEW D 94, 082002 (2016)
Magnetic Monopoles
(flux upper limits)

 PHYSICAL REVIEW D 94, 082002 (2016)
Summary

Energy Spectrum: Ankle and flux suppression consistent with GZK cutoff observed

Arrival directions: No significant correlation observed with nearby astrophysical objects. However, a significant large scale anisotropy (dipole type) has been observed at higher energies.

Mass Composition: - At around $10^{17}$ eV the composition is mixed and dominated by heavier elements.
  - The composition gets lighter with energy and at $10^{18.3}$ it reaches it is dominated by lighter elements.
  - Above $10^{18.3}$ the composition gets heavier with energy and the dispersion of masses is reduced.

Hadronic Models: High energy hadronic interaction models are not describing correctly the observed muonic component of air showers.

Photons/Neutrinos: No sources of high energy photons/neutrinos have been observed. Constraining upper limits for diffuse fluxes have been estimated.

Magnetic monopoles: No candidates have been observed. Auger large exposure allows to estimate the most constraining flux upper limits.

Future: The Auger collaboration has entered a new phase. New complementary detectors (scintillators on top of the water tanks and also buried underground) are being deployed. In addition a radio antennas array have been deployed. The aim to record precise measurements of the electromagnetic and muonic components of the air showers. This will help to understand the deficiencies observed in the hadronic models.
Correlation between $X_{\text{max}}^*$ and $S^*(1000)$

Ranking coefficient $r_G$ [R. Gideon, R. Hollister, JASA 82 (1987) 656]

1. rank events in $X_{\text{max}}^*$ and $S^*(1000)$

2. replace measured values by ranks:
   \[ X_{\text{max}}^*(1), \ldots, X_{\text{max}}^*(N) \Rightarrow 1, 2, \ldots, N \]
   \[ S^*(1000)(1), \ldots, S^*(1000)(N) \Rightarrow 1, 2, \ldots, N \]

3. count events with ranks deviating from the expectations for perfect (anti-)correlation; all events contribute 0 or 1 $\Rightarrow$ robustness against outliers

$r_G$ is invariant to any transformations leaving ranks unchanged
  e.g. to systematics in $X_{\text{max}}^*$ and $S^*(1000)$

various coefficients applied (incl. Pearson, Spearman), conclusions unchanged
Angular Resolution

Hybrid Angular resolution (68% CL)
0.5 degrees above 1EeV

Surface array Angular resolution (68% CL)
< 1.6° for 3 station events (E> 3EeV, θ < 60°)
< 1.2° for 4 station events
< 0.9° for 6 or more station events
Event Reconstruction
Arrival direction, energy and mass

Geometry
(arrival direction)

- from timing and position information of the triggered SD stations.
- For the subset of events that also triggered the FD (hybrid events): from pixel timing, pixel FOV direction and position and timing of only the brightest SD station.

With SD

Station trace

With FD

Shower Longitudinal profile

The $X_{\text{max}}$ resolution is in average 20 g/cm$^2$

Calorimetric metric measurement of the energy
The Cosmic Ray Energy Spectrum

Four independent measurements

Declination dependence
The expected shower profile (measured by the FD) for proton and Iron are different.

Note: $X_{\text{max}}$ is used to characterize the shower profile.
X_{\text{max}} distribution fits

**Sibyll 2.1**

- $p + \text{Fe}$
- $p + \text{N} + \text{Fe}$
- $p + \text{He} + \text{N} + \text{Fe}$

**QGSJET II-04**

- $p + \text{Fe}$
- $p + \text{N} + \text{Fe}$
- $p + \text{He} + \text{N} + \text{Fe}$

**EPOS-LHC**

- $p + \text{Fe}$
- $p + \text{N} + \text{Fe}$
- $p + \text{He} + \text{N} + \text{Fe}$

*PHYSICAL REVIEW D 90, 122006 (2014)*

45
$X_{\text{max}}$ moments from HEAT and from standard FD measurements

![Graph showing average and standard deviation of $X_{\text{max}}$ vs. log$_{10}(E/\text{eV})$.]

**Average of $X_{\text{max}}$**

- HeCo dataset
- Standard dataset

**Std. deviation of $X_{\text{max}}$**

- HeCo dataset
- Standard dataset

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Standard FD  →  PHYSICAL REVIEW D 90, 122005 (2014)
Resolution and systematics of the reconstructed $X_{\text{max}}$ for HEAT

Note: The detector resolution is estimated using simulations.
FIG. 1. Geometry used to obtain the muon traveled distance and the time delay.

\[ z \approx \frac{1}{2} \left( \frac{r^2}{c(t - \langle t_e \rangle)} - c(t - \langle t_e \rangle) \right) + \Delta - \langle z_\pi \rangle, \quad (1) \]

where the geometric delay \( t_g \) has been approximated by \( t_g \approx t - \langle t_e \rangle \).

For each point at the ground, Eq. (1) gives a mapping between the production distance \( z \) and the arrival time \( t \) of muons. The production distance can be easily related to the production depth \( X^\mu \) (total amount of traversed matter) using

\[ X^\mu = \int_z^\infty \rho(z') \, dz', \quad (2) \]
Muon Production Depths (MPD) profiles

$X^\mu_{\text{max}}$

$r = 2194 \text{ m}$
FIG. 7 (color online). Evolution with energy of the mean and rms of the distribution $X_{\text{max}}^{\mu} \text{(reconstructed)} - X_{\text{max}}^{\mu} \text{(true)}$. The simulations were made using the QGSJETII-04 [30] and EPOS-LHC hadronic models for protons and iron nuclei for $55^\circ \leq \theta \leq 65^\circ$. Dashed lines indicate the final systematic uncertainty bounds due to the reconstruction effects, different hadronic models, and primary particles.

TABLE II. Evaluation of the main sources of systematic uncertainties in $X_{\text{max}}^{\mu}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sys. uncertainty [g/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction, hadronic model and primary</td>
<td>10</td>
</tr>
<tr>
<td>Seasonal effect</td>
<td>12</td>
</tr>
<tr>
<td>Time variance model</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
</tr>
</tbody>
</table>
Expected $X_{\text{max}}^\mu$ distribution for proton and Iron

FIG. 4 (color online). $X_{\text{max}}^\mu$ distributions for proton and iron showers simulated at 30 EeV with EPOS-LHC at zenith angles between 55° and 65°. The mean value and the rms of the distributions show a clear dependence on the mass of the primary cosmic ray. For the construction of the MPDs, only muons reaching the ground at distances greater than 1700 m were considered.