Results of the Pierre Auger Observatory after 10 years of operation

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Outline

Review of some of the latest results

- Energy spectrum
- Anisotropy
- Mass composition
- Photons and neutrinos

Future perspectives (see R. Smida’s talk)
The Pierre Auger Observatory

Surface Detector array (SD)
particle density at ground
1600 + 60 water Cherenkov stations, surface of 3000 km², 1.5 km spacing
100% duty cycle

Fluorescence Detector (FD)
longitudinal profile
10-15% duty cycle

24 telescopes in 4 buildings,
FoV: 1- 30° in elevation

+ 3 High Elevation Auger Telescopes (HEAT)
FoV: 30- 60° in elevation (in tilted mode)

Total surface: 3000 km²
Taking data since 2004, completed in 2008

Hybrid events: at least 1FD + 1SD
The hybrid concept

SD event \( \geq 3 \) stations

**SD:** Lateral distribution of secondary particles at ground

- signal at 1000 m \( S(1000) \rightarrow \) energy
- energy calibration from FD in hybrid events

**FD:** Longitudinal development calorimetric energy
The hybrid concept and the energy scale

- Wide energy range covered
  - **SD infill**: spacing 750 m (E > 10\(^{17}\) eV)
  - **SD**: spacing 1500 m (E > 10\(^{18.5}\) eV)
  - **horizontal** (zenith > 60\(^{\circ}\))
  - **Hybrid**: (E > 10\(^{18}\) eV): not shown in the plot

- Common energy scale (from FD)
  - SD energy calibrated with hybrids
  - **systematic uncertainties** on the energy scale: 14% at E > 10\(^{18}\)eV

- Combined spectrum above 10\(^{17}\) eV

- Exposure: ~ 50000 km\(^2\) sr y
The energy spectrum

\[
E_{\text{ankle}} \ [\text{EeV}] = 4.82 \pm 0.07
\]

\[
E_{s} \ [\text{EeV}] = 42 \pm 1.7
\]

\[\gamma = 2.60\]

\[\gamma = 3.29\]

Flux suppression at more than 20 \(\sigma\)

syst. uncert. on energy scale ~ 14%
The energy spectrum

\[ E_{\text{ankle}} [\text{EeV}] = 4.82 \pm 0.07 \]
\[ E_s [\text{EeV}] = 42 \pm 1.7 \]
\[ \gamma = 2.60 \]
\[ \gamma = 3.29 \]

Flux suppression at more than 20 \( \sigma \)

To discriminate between different scenarios:

- **mass composition** on event-by-event basis
- cosmogenic **photons** and **neutrino**
Arrival directions

Autocorrelation (search for pairs of events): look for excesses of “self clustering”

All-sky search: look for localized excesses of events

- High degree of isotropy challenging the original expectation of few sources and light primaries
- The most significant deviation from isotropy are at intermediate angular scales
Large scale anisotropy

Harmonic analysis in right ascension and azimuth (declination sensitive)
~ 70k events with E > 4 EeV and θ < 80°. Two energy bins (4 < E < 8 EeV and E > 8 EeV)

Dipole amplitude: 7.3 ± 1.5%, Pointing to (95° ± 13°, -39° ± 13°)

Indication of a dipole at E > 8 EeV
Challenging the original isotropy expectation at these energies
Complementary measurements

- **Longitudinal profile with THE FD**
  - direct observation of $X_{\text{max}}$
  - average composition from **1st and 2nd moments of the $X_{\text{max}}$ distribution**
  - abundances of masses from fit of the $X_{\text{max}}$ distribution

- **Muon counting with the SD**
  - Muon density at ground
  - Temporal structure SD traces

- **Complementarity**
  - constrain **hadronic interaction models**
FD standard analysis \((E > 10^{17.8} \text{ eV})\)
- ~8 years of data (2004 - 2012)
- Good detector and atmospheric conditions
- Good profile reconstruction
- \(X_{\text{max}}\) observed in the field of view

Extension to low energies \((E > 10^{17} \text{ eV})\)
- 2010 - 2012: HEAT + 1 FD (Coihueco site)
  - \(X_{\text{max}}\) difference HEAT-FD compatible within systematics

Fiducial cuts
- Cut to avoid biases in the distribution of \(X_{\text{max}}\)
- Correction for FD acceptance

systematic uncertainties: \(~ 15 \text{ g/cm}^2\)
**Xmax measurement with the FD**

**Depth of shower maximum (Xmax)** proportional to the lnA.
Mass inferred from the first two moments of the Xmax distribution

Break-point @ E \(\sim 10^{18.3}\) eV: Mass composition from intermediate to light primaries at low energy and to intermediate/heavy at high energy

*A. Porcelli for the Pierre Auger Coll., ICRC 2015*
Interpretation of results: conversion to $<\ln A>$

$X_{\text{max}}$ converted to $<\ln A>$ based on simulations

<table>
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<th>Analysis method</th>
<th>Systematic Uncertainties</th>
<th>Results</th>
<th>Conclusions</th>
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<tbody>
<tr>
<td>A. Porcelli for Pierre Auger</td>
<td>$X_{\text{max}}$ above $10^{17}$ eV with the FD of the Pierre Auger Observatory (CR-EX 1176 – PoS 420)</td>
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Low energy: from intermediate to light

High energy: from light to heavy

- Many components
- Dominated by one/a few components

![Graphs showing data distribution](image)

Epos-LHC

Fe

mixed 50% p 50% Fe

pure composition

unphysical region

$\ln A$ converted to $X_{\text{max}}$ based on simulations
Interpretation of results: conversion to $\langle \ln A \rangle$

$X_{\text{max}}$ converted to $\langle \ln A \rangle$ based on simulations

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<th>Energy</th>
<th>From</th>
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<td>High</td>
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QGSJet II.04

Compatible results between QGSJet II.04 and Epos-LHC

Unphysical results at high energy!
QGSJet-II.04 disfavored (even if still compatible within syst. uncert.)
Are the moments of $X_{\text{max}}$ distribution enough?


Same $X_{\text{max}}$ and $\sigma(X_{\text{max}})$ but different mixtures

fit the $X_{\text{max}}$ distribution with a $N$-components model
Mass composition (up to 40 EeV)

Hybrid data (E > 10^{17.8} eV)

Muon counting with inclined events (62-80°)

- EM component mostly absorbed in inclined events
- Reconstruction based on muon density templates

Muon scale: \[ R_\mu = \frac{N^\text{data}_\mu}{N^\text{MC}_\mu} \]

- Muon deficit in simulations (from 30% to 80% @ 10^{19} eV depending on models)
- Uncertainties too large to make conclusions on mass
Combined fit: spectrum and mass composition

**Model:** identical sources (uniformly distributed) accelerating p, He, N, Fe

**Fit parameters:** injection flux, spectral index, energy cut off, mass fractions

Best fit with very hard spectra ($\gamma \leq 1$)
Prevailing intermediate mass at the source
UHE photons

Photon limits 95% C.L.

- GZK p (Gelmini '08)
- GZK p (Kampert '12)
- GZK Fe (Kampert '12)

- SHDM
- SHDM'
- TD
- ZB

- Hyb
- HP
- TA 2013
- TA 2015 (preliminary)
- SD 2008
- SD 2015 (preliminary)

✓ top-down models disfavored
✓ GZK flux region within reach
\( \nu \) selected as inclined showers with large em component (time spread of SD signals)

- Waxman-Bahcall landmark reached
- Cosmogenic model with pure p composition at the source and strong FRII evolution disfavored
Summary of results

After 10 years of operation, the Pierre Auger Observatory has answered to some long-standing questions and has opened new ones:

- **Ankle** position and **flux suppression** at high energy observed with high significance

- **mass composition** measured over a wide energy range:
  - predominantly mixed with a break around $10^{18.3}$ eV

- Data and air-shower models **discrepancies in the number of muons**

- Doing **astronomy with UHECRs** is becoming more and more challenging

- UHE **photons and neutrinos** disfavor exotic models and are reaching the sensitivity to test the GZK expected fluxes
AugerPrime: A needed step to proceed further

1. Elucidate the origin of the flux suppression (energy-loss vs. maximum-energy scenarios)
   - Fundamental constraints on UHECR sources
   - Galactic vs. extragalactic sources
   - Prediction of GZK neutrino and photon fluxes

2. Search for a flux contribution of protons at ~10% level up to highest energies
   - Prospects for future UHECR experiments
   - Proton astronomy and anisotropy searches

3. Increase sensitivity to neutrino and photon detection
   - Improved limits on exotic models
   - Discovery potential

4. Study of extensive air showers and hadronic multiparticle production
   - Particle physics beyond man-made accelerators
   - Search / constraints on new physics phenomena (LIV)

(see R.Smida’s talk)
Backup slides
Fitting the $X_{\text{max}}$ distributions

Hybrid data ($E > 10^{17.8} \text{ eV}$)

fit the $X_{\text{max}}$ distribution with a \textit{$N$-components model}

\[
C_j = \frac{N_{\text{data}}}{N} \sum_s f_s X_{s,j}^m,
\]

fraction of the specie $s$
Resolution and systematic uncertainties

A. Porcelli for the Pierre Auger Coll., ICRC 2015

- reconstruction bias (only left) and detector resolution (right)
- offset in time between SD-FD, calibration and telescopes alignment
- analysis
- atmospheric uncertainty in the geometry reconstruction and fluorescence light yield
Comparing Auger and Telescope Array

1) Construct a model of $X_{\text{max}}$ distribution describing the Auger data (based on the fit of $X_{\text{max}}$ distributions)

![Graph of $X_{\text{max}}$ distribution and its fit](image)

2) Pass the "Auger-like" composition through the TA detector simulation and reconstruction/analysis chain

*caveat: only QGSJet II.04 hadronic model used so far*
Comparing Auger and Telescope Array

Auger:
- 8 years
- hybrid (at least one surface detector station)
- 24 telescopes
- PRD 90 (2014) 12, 122005

TA:
- 5-year hybrid data sample
- hybrid (at least three surface detector station)
- Middle Drum telescopes (MD)
- APP 64 (2014) 49

M. Unger et al. for the Pierre Auger and Telescope Array Collaborations, ICRC 2015
AugerPrime: timeline and exposure

Timeline
April 2015: preliminary design report
March 2016: engineering array
2017-2018: deployment
2018 - 2024: data taking

| log_{10}(E/eV) | dN/dt|infill [yr^{-1}] | dN/dt|SD [yr^{-1}] | N|infill [2018-2024] | N|SD [2018-2024] |
|---------------|--------|-----------------|---------|----------------|-----------------|
| 17.5          | 11500  | -               | 80700   | -              |
| 18.0          | 900    | -               | 6400    | -              |
| 18.5          | 80     | 12000           | 530     | 83200          |
| 19.0          | 8      | 1500            | 50      | 10200          |
| 19.5          | \sim1  | 100             | 7       | 700            |
| 19.8          | -      | 9               | -       | 60             |
| 20.0          | -      | \sim1           | -       | \sim9          |
Cross-Checks HEAT - Coihueco

Figure 2: \( X_{\text{max}} \) difference between CO and HEAT (in downward mode) in MC simulation (red histogram) and data (blue dots).

In this paper, nearly two years of calibrated HEAT data, from 01.06.2010 to 15.08.2012, are used to extend the previous measurement of the \( X_{\text{max}} \) moments \[1\] from 10\(^{17}\) eV down to 10\(^{17}\) eV.

2. Data analysis

The analysis presented in this paper is based on two datasets. The data collected by the standard FD telescopes during the period from 01.12.2004 to 31.12.2012 (published in \[1\]), and the data collected with HEAT and Coihueco telescopes (HeCo) during the period from 01.06.2010 to 15.08.2012.

HEAT can be operated in upward and downward modes. The downward mode is when the telescopes are oriented such that their elevation angle extends up to 30\(^\circ\) (same as the standard Auger telescopes). The upward mode is when they cover an elevation angle ranging from 30\(^\circ\) to 60\(^\circ\) (this is the HEAT standard operation mode). The HEAT downward mode is used for systematic cross checks, because it allows one to observe the same showers in coincidence with telescopes from the Coihueco site. In Figure 2 the \( X_{\text{max}} \) difference between CO and HEAT in downward mode is shown.

Data (blue dots) and simulations (red lines) are in agreement, which implies a good knowledge of the detector.

The standard FD dataset contains events with energies above 10\(^{17}\) eV and the HeCo one contains events with energies above 10\(^{17}\) eV. HeCo runs out of statistics at energies beyond \( E < 10^{18} \) eV.

In order to combine two statistically independent datasets, we have removed from the standard FD dataset all Coihueco events with energies below \( E < 10^{18} \) eV and recorded during the HeCo period (from 01.06.2010 to 15.08.2012). This cut has reduced the standard FD data by only 1377 events (out of 19759 events).

2.1 Data selection

The analysis is based on hybrid events, i.e. on events with geometries reconstructed using information on arrival times of both light in the cameras of FD telescopes and of the shower front at ground as measured by the ground station closest to the shower axis. We selected data recorded during the period from 01.06.2010 to 15.08.2012.

\[ X_{\text{max}} \] difference between HEAT and FD (Coihueco site)

- compatible within systematics
- good agreement data/MC

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>464</td>
<td>1296</td>
</tr>
<tr>
<td>Mean</td>
<td>2.3±1.8</td>
<td>2.0±1.1</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>38.1±1.4</td>
<td>38.5±0.9</td>
</tr>
</tbody>
</table>
Muon counting with vertical events

**Muons with zenith angles < 60°**

*Hybrid events used to test LHC-tuned hadronic models*

Ground signal modified in MC to fit the one in the data

**Rescaling factors:**

- $R_E$ → primary energy
- $R_{\text{had}}$ → hadronic contribution to the ground signal

**Analysis details:**

- data set: 01/2004 - 12/2012
- $E = 10^{18.8} - 10^{19.2} \text{ eV}$
- zenith angles [0°, 60°]
- 411 hybrid events after quality cuts
- Systematic Uncertainties on $R_E$ and $R_{\text{had}}$: 10%
UHE neutrino

ν selected as inclined showers with large em component (time spread of SD signals)

- **down-going**

  ![Diagram of down-going showers](image)

  Energy of shower ~ 5 EeV
  Distance to shower axis ~ 1 km
  Zenith angle ~ 80° (“old shower”)

  ![Old shower](image)

  ![Young shower](image)

- **up-going (Earth-Skimming)**

  ![Diagram of up-going showers](image)

  ντ flavor
  Earth-Skimming (90°, 95°)
  contrib. to total evt rate 73%

ν identification applied “blindly” to data: 01/2004 - 12/2012

No candidates found!

Low zenith (65°,75°)
contrib. to total evt rate: 23%

High zenith (75°,90°):
contrib. to total evt rate: 4%
An international effort

Argentina
Australia
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherland
Poland
Portugal
Romania
Slovenia
Spain
UK
USA
Colombia (associated)
Boliva, Peru (Lol)

~ 500 Collaborators; 88 Institutions; 17 countries
The Scintillator Surface Detector

- $S_\mu$ from WCD and SSD signals
  - $\sigma[S_\mu(800)] / \langle S_\mu(800) \rangle \sim 15\%$ (iron)-20\% (proton)
- resolution $X_{\text{max}} \sim 30$ g/cm$^2$

Scintillation detector (SSD)

Water-Cherenkov detector (WCD)

$S_{\mu,\text{WCD}} = aS_{\text{WCD}} + bS_{\text{SSD}}$

- faster sampling (120 MHz)
- enhanced trigger and monitor capabilities