High Energy Cosmic Rays
at the Pierre Auger Observatory
after 10 years: results and future

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IPN Orsay, Université Paris XI, CNRS/IN2P3
The Pierre Auger Collaboration

460 collaborators
110 institutions from 17 countries

Argentina – Australia – Brazil – Colombia – Czech Republic – France – Germany – Italy – Mexico – Netherlands – Poland – Portugal – Romania – Slovenia – Spain – United Kingdom – United States
Outline

The Pierre Auger Observatory
Science case and characteristics

Results, towards the understanding of UHECR’s
Spectrum,
Anisotropy
Mass composition
Hadronic models

Summary and future plans
Auger Prime
Original AUGER Science Case

1. A precise reconstruction of the **energy spectrum**
   Is the GZK cutoff observed or challenged?

2. The **identification of primaries**, even if only statistical:
   proton, nuclei, or more exotic particles ([gamma, neutrinos?])
   - Based on the air shower properties,
   - Could give constrain to existing hadronic models

3. A systematic study of **arrival directions**
   Search for indication of anisotropies and existence of point sources
The Pierre Auger Observatory in Argentina

**Surface detectors**
- 1680 Cherenkov stations
- 1.5 Km spaced on a hexagonal grid
- Can detect shower up to 90°
- 100% duty cycle

**Fluorescence detectors**
- 4 building with 6 telescopes each
- Telescope f.o.v. 30 x 30
- ~15% duty cycle

Completed in 2008
Progressive data taking starting in 2004

Aiming at understanding the origin of Ultra High Energy Cosmic Rays, the PAO associates the widest detection surface (3000 km$^2$) together with the highest precision ever achieved.
Shower Observables recorded

Time structure

Lateral distribution

Longitudinal profile

\[ E \propto \int \frac{dE}{dX} dX \]

\[ S_{1000} \propto E \]

\[ \text{signal [VEM]} \]

\[ \text{detector signal (arb. units)} \]

\[ \text{time bins (25 ns)} \]

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Present status of the Pierre Auger Observatory

LOW ENERGY EXTENSION ($10^{17} - 3 \times 10^{18}$ eV)

HEAT

Existing tank array 1500m

Coihueco FD

HEAT

Infill array 750m

750 m ARRAY

1500 m ARRAY
Present status of the Pierre Auger Observatory

LOW ENERGY EXTENSION (10^{17} - 3 \cdot 10^{18} \text{ eV})

HEAT

Existing tank array 1500m

Coihueco FD

Infill array 750m

750 m ARRAY

AERA

153 Radio Antennas
Graded 17 km² array
COMPLETED APRIL 2015

Engineering Array of 7 buried muon detectors
COMPLETED FEBRUARY 2015

AMIGA MUON COUNTERS

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The different AUGER data sets

**SD-750 m (θ<55°)**
- Fully efficient: $E > 3 \times 10^{17}$ eV
- Energy estimator: $S_{35}$

**SD-1500 m (θ<60°)**
- Fully efficient: $E > 3 \times 10^{18}$ eV
- Energy estimator: $S_{38}$

**SD-1500 m (62°<θ<80°)**
- Fully efficient: $E > 4 \times 10^{18}$ eV
- Energy estimator: $N_{19}$

**HYBRID**
- FD + ≥ 1 SD 1500 station  Fully efficient: $E \geq 10^{18}$ eV
- HEAT + ≥ 1 SD-750 station Fully efficient  $E \geq 10^{17}$ eV

Energy measurement: EFD
SPECTRUM
Energy Reconstruction of Auger Events

**SD vertical** (θ < 60°)

**Energy estimator **S**(1000):**

Signal at 1000 m from lateral profile

$S(1000)$ is θ dependent due to attenuation in atmosphere

$\rightarrow$ use of Constant Intensity Cut [CIC]

Conversion $S(1000) > S_{38}$

In case of SD 750m array: $S(450) > S_{35}$

**SD horizontal al** (62 < θ < 80°)

**Energy estimator : $N_{19}$**

$N_{19}$: relative number of muons at ground w.r.t. the density of muons of the reference distribution:

$\rho_{\mu,19}$ reference profile from parameterization of muon density at ground ( $10^{19}$ eV per QGSJetII-03)

$N_{19}$ is not θ dependent (already included in $\rho_{\mu,19}$)

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Calibration of AUGER data sets

For each SD data, the energy estimator is calibrated with FD energy with hybrid data set.

Cross correlation of the SD energy estimators ($S$) with the FD energy:

$$E_{FD} = A \times S^B$$

<table>
<thead>
<tr>
<th>Detector</th>
<th>$E$</th>
<th>$N \ (E&gt;E)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid FD+SD</td>
<td>1</td>
<td>~10000</td>
</tr>
<tr>
<td>SD 1500m (0°-60°)</td>
<td>3</td>
<td>~100000</td>
</tr>
<tr>
<td>SD 1500m (60°-80°)</td>
<td>4</td>
<td>15000</td>
</tr>
<tr>
<td>SD 750m (0°-55°)</td>
<td>0.3</td>
<td>6000</td>
</tr>
<tr>
<td>HEAT +SD</td>
<td>0.1</td>
<td>60000</td>
</tr>
</tbody>
</table>

The FD defines all energy scales -> systematic uncertainty ~ 14%
Energy spectrum over 3 decades in energy

4 data sets combined: SD 750 m FD (hybrid) SD 1500 m (0-60°), SD 1500 m (60-80°)

≈ 200 000 events, ≈ 50000 km² sr yr exposure, FOV: -90°, +25 in δ

\[ \gamma_1 = 3.29 \pm 0.02 \pm 0.05 \]
\[ \gamma_2 = 2.6 \pm 0.02 \pm 0.1 \]
\[ \Delta \gamma = 3.14 \pm 0.02 \pm 0.04 \]

\[ E_{\text{ankle}} = (4.8 \pm 0.1 \pm 0.8) \text{ EeV} \]
\[ E_{\text{supp}} = (42.1 \pm 1.7 \pm 7.6) \text{ EeV} \]
Discrepancy can be accommodated within a systematic energy shift, but not at the highest energies

Under study by UHECR spectrum WG(TA/Auger) (I.C Maris, UHECR2014)
ANISOTROPIES
The search for anisotropies to track the origin of cosmic rays

At small and intermediate scale:

For light particles at the largest energies we expect small deviation from magnetic fields (a few degrees):
- A clear anisotropy would reveal a large fraction of protons in the high energy flux
- Possible CR astronomy??

> Intrinsic correlations or correlation with close objects from catalogs

At large scale:

- Diffusion & escape of galactic CR below EeV energies can generate dipole pattern

- A change in the large scale anisotropy could sign the galactic/extra galactic transition (at the ankle?)

> Search of dipole on different energy ranges
Scan on parameters: compute the obs./exp number of events in each circular window for:

\[ E_{\text{th}} \in [40;80] \text{EeV} \text{ in } 1 \text{ EeV steps, } \Psi \in [1;30] \] \text{ in } 1^\circ \text{ steps}

Li-Ma significance map in 12° circles;
largest excess 4.3\sigma, Ethresh = 54 \text{ EeV}, 18^\circ \text{ from CenA};
Post-trial probability (from simulations ) 69%,

All excess found are compatible with isotropy.
Search of small/intermediate scale anisotropies in the arrival directions of the most energetic cosmic rays < 80°

Search of correlations with astrophysical structures Gal-Xgal planes, 2MRS galaxies, Swift-BAT AGNs, jetted radio galaxies, CenA; Scan over angles, $E_{\text{thresh}}$, luminosity for AGNs and radio galaxies.

Largest excess of pairs for Swift AGNs with $E_{\text{thresh}} = 58$ EeV, 18° circles, $L > 10^{44}$ erg/s, closer than 130 Mpc; post-trial probability 1.3%.

No statistically significant deviation from isotropy

Large scale anisotropies

Auger data set: \(\approx 70000\) events with \(E > 4\) EeV and \(\vartheta < 80^\circ\), 85% sky coverage

- Modified Raleigh or East-West analysis on 1500 m and 750 m arrays dataset

Auger/TA: \(\approx 17000\) Auger events, \(\approx 2500\) TA events with \(E > 10\) EeV, Full sky coverage

Spherical harmonic analysis

\[C_\ell = \frac{1}{2} \ell + 1 \hat{A}_\ell = \ell |a_\ell|^2.\]

In the same way as the multipole coefficients, any significant anisotropy of the angular distribution over scales near \(1/\ell\) radians would be captured in a non-zero power in the mode \(\ell\). Although the exhaustive information of the distribution of arrival directions is encoded in the full set of multipole coefficients, the characterisation of any important overall property of the anisotropy is hard to handle in a summary plot from this set of coefficients. Conversely, the angular power spectrum does provide such a summary plot. In addition, it is possible that for some fixed mode numbers \(\ell\), all individual \(a_\ell\) coefficients do not stand above the background noise but meanwhile do so once summed quadratically.

From the set of estimated coefficients \(\bar{a}_\ell\), the measured power spectrum is shown in fig. 4.

The gray band stands for the RMS of power around the mean values expected from an isotropic distribution.

\[\text{AUGER/TA} \quad \text{Dipole Amplitude: } 6.5 \pm 1.9\% \quad (p=5\times10^{-3})\]

Pointing to \((a, d) = (93^\circ \pm 24^\circ, -46^\circ \pm 18^\circ)\)

Indications of large-scale anisotropies of CRs at \(E > 8-10\) EeV challenging the original expectations of isotropy at these energies
MASS COMPOSITION
Composition from FD longitudinal profile

Fe shower develop higher in atmosphere -> lower X_{max} (\sim 100 g/cm^2 avrg)

Observables sensitive to composition:

- Depth of shower maximum \langle X_{max} \rangle;
- Elongation rate (d\langle X_{max} \rangle/d\log E);
- RMS of X_{max} distribution at fixed energy;

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Mass composition over 3 decades in energy- $X_{\text{max}}$

✓ From a clean hybrid data set (strong anti-biais cuts), detector independent measurement
✓ Latest Hadronic interaction MCs tuned to 7 EeV LHC data
✓ New extended low energy range data down to $10^{17}$ with HEAT FOV

In agreement with TA when folded from the detector effect (as done in TA)

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From $X_{\text{max}}$ to primary mass $\langle \ln (A) \rangle$

\[\langle \ln A \rangle = \ln 56 \frac{X_{\text{max}}^p - \langle X_{\text{max}} \rangle}{X_{\text{max}}^p - X_{\text{max}}^Fe}\]

Similar trend with energy for both models: heavy, lighter heavier
Also tests of models -> QGSJET II yields unphysical results
Spectrum and $X_{\text{max}}$

Combined fit of energy spectrum and $X_{\text{max}}$ using propagation models

Homogeneous distribution of identical sources of $p$, He, N and Fe nuclei;
125 data points, 6 fit parameters: injection flux norm. and spec. index $\gamma$, cutoff rigidity $R_{\text{cut}}$, $p$/He/N/Fe fractions;

Combined fit of Auger spectrum and composition data

For details, see R. Alves Batista, D. Boncioli, A. di Matteo, A. van Vliet and D. Walz, “Effects of uncertainties in simulations of extragalactic UHECR propagation, using CRPropa and SimProp, prepared for submission to JCAP” [coming soon on arXiv]

$\rightarrow$ Best fit with very hard injection spectra ($\gamma \leq 1$).
Neutrino and photon at EeV energies?

Use observables from SD to select neutrinos or photons

**Neutrinos**
- Use footprint of the shower and time structure of the signal

**Photons**
- Use later profile of the shower and time structure of the signal

First limit from an EAS array below WB bound

Top-down models strongly disfavoured

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MUONS IN SHOWERS
AND
HADRONIC MODELS
Muon in showers and hadronic models

Composition with SD need reliable hadronic models ->
Comparison of muon number to models with different data using FD and SD

- Measurement of muon number in highly inclined air showers (SD+FD)
  from E-FD and mean muon scale
  \[ R_\mu = \frac{N_{\mu,\text{data}}}{N_{\mu,\text{MC}}} \]

- Measurement of the longitudinal depth of the muon component (SD only)

Muon Production Depth inferred from the SD traces for inclined showers

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Muon content of very inclined showers and hadronic models

\[ <R_\mu> \text{ vs Energy} \]

\[ <R_\mu> \text{ vs } X_{\text{Max}} \]

\[ <R_\mu> \text{ higher than MC iron predictions} \]

Tension between the Xmax and muon measurements

Deficit of muons in simulations between 30% and 80%

PRD91,032003, 059901 (2015)

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Muon production depth and hadronic models

\[ \ln(A) \text{ deduced from } X^\mu_{\text{max}} \text{ are compared to } \ln(A) \text{ from } X_{\text{max}} \text{ from FD} \]

Values compatible within 1.5 \( \sigma \) for QGSJetII-04
incompatible at > 6 \( \sigma \) for Epos-LHC

SUMMARY

AND

FUTURE
Summary and open issues after 10 years of data taking and analysis

✓ Clear flux suppression above 40 EeV (>20 s):
   but GZK or end of acceleration power at the sources?

✓ Towards a heavier mass when going to the highest energies:
   but statistics limited by FD only data
   and SD composition data in tension with FD and/or hadronic models

✓ Stringent photon source limit favor astrophysics source but no clear isotropy found at the highest energy: the hypothesis of few sources of light primaries is challenged

Need to select light primaries to do Cosmic ray astronomy

COMPOSITION MEASUREMENTS EVENT BY EVENT, UP TO THE HIGHEST ENERGIES, WITH THE LARGE SD STATISTICS IS ABSOLUTELY NEEDED!

Objective of Auger future upgrade, AUGER-Prime
Primary cosmic Ray Identification with Muons and Electron

Extended FD duty cycle
Installation of a Scintillator Surface Detector (SSD) on top of each WCD
Upgraded SD Electronics

Foreseen schedule

- PDR ready since April 2015
- EA planned for March 2016
- Data taking 2018-2024 (40 000 km² sr yr)
The SSD methodology

Sampling of the shower particles with two detectors having different responses to muons and electromagnetic particles.
AUGER Prime Science Case

1. A precise reconstruction of mass dependant energy spectrum

2. The identification of primaries, event by event, up to the highest energies

3. A systematic study of arrival directions of an enhanced proton data sample

...to access the global picture of the origin of HECR and UHECR
Thank you
Galactic neutron searches

Motivation:

- Neutrons of 1 EeV can reach us from \( \sim 9 \) kpc \( (d = 9.2 \text{ E[EeV]} \text{ kpc}) \)
- Produced by protons in pion-producing interactions with ambient photons, protons or nuclei, also producing gamma rays
- Travel without deflections
- Air showers indistinguishable from protons

Methods:

**Blind search:**

NO significant point-like (at the angular resolution) over-density found
\( \rightarrow \) sources are extragalactic, or transient, or optically thin to escaping protons, or weak & densely distributed

**Search for point-like excess** of EeV CRs around different stacked sets of sources (HESS, Fermi sources, X-ray binaries, pulsars, Galactic Plane and Galactic center, magnetars, microquasars, etc.):

NO candidate found with significant excess
\( \rightarrow \) Flux \( (>1\text{EeV}) < 0.01 \text{ km}^{-2} \text{ yr}^{-1} \)
σ_{p\text{-air}} cross-section for deep showers, rising with E, measured at $\sqrt{s} \sim 39, 56$ TeV.
FLUORESCENCE YIELD

Update of the absolute intensity of the 337 nm band (absolute normalisation of the wavelength spectrum)

**Now AIRFLY**: 4% uncertainty
M. Ave et al., Astropart. Phys. 42 (2013) 90

**Before**: 14% uncertainty

\[ \Delta E/E \approx 3.4\% \]
(before we had 14%)
Mass composition - $X_{\text{max}}$

Change from a mixed/light composition to a heavier one
New Energy scale from FD Energy

Changes in: Atmosphere, fluorescence yield, invisible energy, FD calibration
Longitudinal profile fit (at ICRC2013)

at $10^{18}$ eV

<table>
<thead>
<tr>
<th>Absolute fluorescence yield</th>
<th>-8.2%</th>
</tr>
</thead>
<tbody>
<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>

Still compatible with former uncertainty (22%)
<table>
<thead>
<tr>
<th>Source of Uncertainty</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><strong>3.6%</strong></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><strong>3.4% / 6.2%</strong></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><strong>9.9%</strong></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><strong>6.5% / 5.6%</strong></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><strong>14%</strong></td>
</tr>
</tbody>
</table>

FD uncertainties propagate to the SD energies

TOTAL ≈ 14%

~ independent of energy
Data selection: $\theta > 55^\circ$, traces from tanks between 1700 and 4000m only to avoid EM contamination.
Mass composition from SD - MPD

Gaisser Hillas profile → $X_{\mu_{\text{max}}}$

- Novel approach to study longitudinal profile
- Agree with conclusion of $X_{\text{max}}$ (but compatible with constant composition)
- Needs to be extended to more data (find methods to measure muons directly)
Interpreting $X_{\text{max}}$ and $X_{\mu_{\text{max}}}$

\[
\langle \ln A \rangle = \ln 56 \frac{X_{\mu_{\text{max}}} - \langle X_{\text{max}} \rangle}{X_{\mu_{\text{max}}} - X_{\mu_{\text{max}}}^{Fe}}
\]

\[
\langle \ln A \rangle^\mu = \ln 56 \frac{X_{\mu_{\text{max}}}^p - \langle X_{\mu_{\text{max}}} \rangle}{X_{\mu_{\text{max}}}^p - X_{\mu_{\text{max}}}^{Fe}}
\]

Data are not consistently reproduced by models

QGSJetII-04

Epos-LHC

Phys Rev D90(2014)012012
Muon deficit in inclined showers

$R_\mu$ is $N_{19}$, the estimated number of muons, corrected from hadronic model dependency ($<3\%$)

Muon numbers predicted by models are under-estimated by 30 to 80% (20% systematic)

arXiv:1408.1421v2
Mass composition - from $X_{\text{max}}$ to $\ln A$

$$\langle X_{\text{max}} \rangle \sim \langle X_{\text{max}}^p \rangle - D_p \langle \ln A \rangle$$
$$\sigma(X_{\text{max}})^2 \sim \langle \sigma_i^2 \rangle + D_p^2 \sigma(\ln A)^2$$

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

D$_p$ elongation rate  $<\sigma_i>$ mass-averaged fluctuations

**Average composition**

$<\ln A> = 4$ pure Fe

$<\ln A> \sim 2$ 50%Fe 50% p

$<\ln A>=0$ pure p

**Dispersion of masses at ground**
(source or propagation)

$\sigma(\ln A)=0$ pure p or Fe

$\sigma(\ln A) \sim 4$ 50%Fe 50% p

- $<\ln A>$ minimum in ankle region
- Energy evolution common to all models $<\ln A>$ increasing from light to medium
- The mix include intermediates species