Results from the Pierre Auger Observatory

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for the Pierre Auger Collaboration
- The Pierre Auger Observatory:  
  *the physics case and the hybrid detector*

- Recent results on:
  - Energy spectrum
  - Mass composition
  - Arrival directions
  - Search for UHE photons and neutrinos
  - Hadronic interactions
  - ...
Investigating the Ultra-High Energy region

Physics Goals
- Sources and Propagation
- Energy spectrum at UHE
- Mass composition

Need for huge exposures in order to have reasonable statistics

H. Bluemer et al, 2009
The Pierre Auger Observatory

- **Surface Detector array (SD)**
  - 1600 water Cherenkov stations, 100% duty cycle

- **Fluorescence Detector (FD)**
  - 24 telescopes, 10-15% duty cycle

Investigate cosmic rays with $E \gtrsim 10^{17}$ eV
- Energy spectrum
- Mass composition
- Arrival direction

Malargüe (Mendoza, Argentina) 1400 m s.l.
The Surface Detector (SD)

The Surface Detector (SD) is a component of the Pierre Auger Observatory, designed to detect the arrival of cosmic rays. It consists of a series of plastic detector tanks filled with 12 tons of water, each equipped with three 9" PMTs. The detectors are spaced 1.5 km apart.

Key components include:
- **GPS antenna**
- **Communication antenna**
- **Solar panel**
- **Electronic enclosure, 40 MHz FADC, local trigger**
- **Battery box**
- **Plastic tank with 12 tons of water**

The Surface Detector is crucial for triggering the observation of high-energy cosmic rays, providing a crucial part of the Pierre Auger Observatory's data collection system.
The Fluorescence Detector (FD)

- 24 telescopes in 4 sites
- Field of view:
  0-30° in elevation
  0-180° in azimuth
- 3 new telescopes (HEAT)

- DAQ scheduled: clear and moonless nights
- **on-time fraction**: weather conditions + DAQ, detector and communication system efficiencies

**duty cycle ~ 12 - 15%**
The hybrid concept

- **FD event**
  - lateral distribution of secondary particles
  - energy proportional to the signal \( S(1000) \) at 1000 m

- **SD event**
  - observation of longitudinal profile
  - calorimetric energy (almost independent of hadronic interaction models)

**FD and SD combined in the hybrid mode**
(i.e. FD + at least 1 SD)

- accurate energy and direction measurements
- complementary mass sensitive parameters
- calibration of the energy scale for SD events using *golden hybrid* data (FD + ≥ 3 SD stations)

\[
E \sim \int \frac{dE}{dX} \, dX
\]
SD energy calibrated with the calorimetric one measured by FD (almost independent of the hadronic interaction models) using the sub-sample of golden hybrid data.

**Attenuation curve (CIC)**

- Convert to $S_{38}$: *$S_{1000}$ that a shower would have produced if it had arrived with a zenith angle of 38°*

- SD energy resolution: $E_{SD}/E_{FD} \sim 15\%$

- Systematic uncertainties:
  - SD calibration: 7% at 10 EeV; 15% at 100 EeV
  - FD energy scale: 22% (dominated by Fluorescence Yield)
Measurement of the energy spectrum

SD Exposure (01/2004-12/2010)
- geometrical calculation (~ 21000 km² yr sr)
- syst. uncertainties: ~ 3%

Hybrid Exposure (11/2005-09/2010)
- time-dependent Monte Carlo simulations
- syst. uncertainties ~10% (6%) at 10^{18} eV (10^{19} eV)

Hybrid spectrum
E > 10^{18} eV
σ_{E/E} ~ 7.6%
FD energy scale

SD spectrum
E > 10^{18.4} eV
σ_{E/E} ~ 15%
FD energy scale
Measurement of the energy spectrum

M.Settimo for the Pierre Auger Collaboration, to be published on EPJ Plus

\[
\log_{10}(E/eV) = 19.63 \pm 0.02
\]
\[
\gamma_2 = 2.63 \pm 0.02
\]
\[
\gamma_1 = 3.27 \pm 0.02
\]
\[
\log_{10}(E_{\text{ankle}}/eV) = 18.62 \pm 0.01
\]

Combined Spectrum

- Hybrid: accurate energy measurement down to \(10^{18}\text{ eV}\)
- SD huge statistics \((E > 10^{18.5}\text{ eV})\)

- Ankle: may indicate a change in the origin of UHECR (galactic to extragal. composition)
- Flux suppression above \(10^{19.5}\text{ eV}\) found with 20 \(\sigma\) significance

syst. FD energy scale 22%

- fluorescence yield 14%
- FD absolute calibration 9.5%
- invisible energy 4%
- reconstruction 10%
- atmospheric effects 8%
Mass composition with FD

**X_{\text{max}}** and **RMS(X_{\text{max}})** measured from the longitudinal profile observed by FD

![Graph showing dE/dX vs. slant depth](image)

- Break of the elongation rate at \( \sim 2.4 \times 10^{18} \text{ eV} \)
- From light to heavier composition at high energy
- Similar indication from RMS(X_{\text{max}}) and measurement using SD data

*significant departure from the predictions of the hadronic models would modify this interpretation*

Dec 2004 - Sep 2010: 6744 hybrid \( E > 10^{18} \text{ eV} \)

\( \sigma_{\text{X_{\text{max}}}} \sim 20 \text{ g/cm}^2 \)

syst. \( \sim 10 - 13 \text{ g/cm}^2 \)
From the **Surface Detector**: 

- $\Theta_{\text{max}}$ Azimuthal asymmetry of the signal risetime

- **Vertical** symmetry in the signals
- **Inclined** asymmetry!!
- **Very inclined** no asymmetry

$\Theta_{\text{max}}$ is defined as the value of $\sec(\theta)$ for the zenith angle that gives maximum asymmetry

18581 SD events (Jan 2004 – Dec 2010)  
$E > 3.16 \times 10^{18}$ eV, and $30^\circ < \theta < 60^\circ$

Muon Production Depth (MPD): the depth, measured parallel to the shower axis, at which a given muon is produced. It can be obtained from the SD signals.

\[ l = \sqrt{r^2 + (z - \Delta)^2} \]

Geometrical delay \((t_d)\): The time difference between the arrival time of the muon and that of the time-reference shower plane.

244 SD events

\( E > 20 \text{ EeV} \)

\( 55^\circ < \theta < 65^\circ \)
Search for anisotropy using nearby AGN (Veron-Cetty Veron Catalog)

28 / 84 events (up to June 2011)

\[ E > \ 55 \text{ EeV} \]
\[ \psi = 3.1^\circ \]
\[ d_{\text{max}} = 75 \text{ Mpc} \]

12 events inside a window of 13\(^\circ\) close to CenA

fraction of correlating events

\[ P_{\text{data}} = 0.33 \pm 0.05 \]

The chance probability of observing such a correlation from a random distribution is below 1 %

- VCV not a complete catalog
- AGN traces the matter distribution
Arrival direction: Centaurus A (aka NGC 5128)

Search in the direction of Cen A, the closest AGN (at 3-5 Mpc)

Excess of correlating events at large energies
Large Scale Anisotropy

Upper limits on the equatorial dipole component start probing anisotropy models

Data on the phase of the first harmonic modulation in right ascension suggest an energy dependence

Search for UHE photons

UHE photons mainly produced as:
- secondaries of the photo-pion production (GZK effect) of nuclei
- product in top-down models for UHECR acceleration

Photons interact with background radiation via $e^+e^-$ production

- closest blazars
- closest AGN
- Galactic center

$\geq 10^{14}$ eV photons absorbed on CMB

\[ \text{photon fraction at Earth} \sim 0.1 - 1\% \]

\[ \text{photon fraction at Earth} \approx 10\% \]
Search for photons with hybrid events

- **FD:**
  - Deeper development of the air showers
    - Larger $X_{\text{max}}$

- **SD:**
  - Smaller detected signal at a given distance
  - Fewer triggered stations

\[ S_b = \sum S_i \left( \frac{R_i}{1000} \right)^4 \]

$S_i$: station signal [VEM]
$R_i$: station distance to the shower axis [m]

details on $S_b$: G. Ros et al., arXiv 1104.3399

\[ \text{Monte Carlo Simulations} \]
\[ \text{Energy} = 10^{18.5} \text{ eV} \]

Search for photons with SD

**Different air shower development for photon primaries:**
- **deeper showers**
- **electromagnetic component**

- Events observed by SD-alone
- radius of curvature $R$ and risetime $t_{1/2}$ at 1000 m used for photons identification

Deviations of data from the mean value of $R$ and $t_{1/2}$ expected for photon showers combined with a Principal Component Analysis

Data sample:
Jan 2004 - Dec 2006

No photon candidates found
Upper limits to the integral photon fraction assuming the Auger Spectrum

0.4%, 0.5%, 1.0%, 2.6% and 8.9% @ E>1, 2, 3, 5 and 10 EeV
Search for neutrinos

Neutrinos/hadron discrimination:

- **inclined events** (elongated footprint at ground) with SD signals typical of
- **young showers** (large contribution of em component)

No candidate found so far

Limits to the diffuse neutrino flux and to point-like sources as a function of their declination

The exponential tail of the $X_{\text{max}}$ distribution is sensitive to proton-air cross section.

\[ \Delta_f = 55.8^{+2.4}_{-2.3} \text{ g/cm}^2 \]

$10^{18} - 10^{18.5} \text{ eV}$

\[ \sigma_{p-\text{air}} = (505 \pm 22_{\text{stat}}^{+20}_{-15})_{\text{syst}} \text{ mb} \]

Systematic uncertainties

- $\Delta$ systematics
- Energy scale
- Hadronic models + simulations
- Composition:
  - $< +10 \text{ mb for } < 0.5\%$ of photons
  - $-12 \text{ mb (-80 mb)}$ for $10\%$ ($50\%$) of He


Ivan De Mitri for the Pierre Auger Collaboration, XIII Marcel Grossmann Meeting, Stockholm, july 6 - 2012
By using the Glauber formalism:
Test of hadronic interaction models

A deficit of muons observed comparing data and Monte Carlo:

- from golden hybrid events
- from inclined events
- independent of the primary particle (i.e. not due to mass composition assumptions)


K.H. Kampert for the Pierre Auger Collaboration, Highlight talk ICRC 2011,
HEAT
Three additional telescopes at the Cohueco site to look up to 60 deg in elevation (closer showers).

Infill array
42 additional SD detectors with 750 m spacing close by the Cohueco site
Low energy event recorder by HEAT and Cohueco:
\[ E \approx 1.7 \cdot 10^{17} \text{eV} ; \theta \approx 19^\circ \]

The Infill Array allows extending the energy range down to \(3 \cdot 10^{17} \text{eV}\)
AUGER Muons and Infill on the Ground Array AMIGA

Infill SD tanks (see previous slides) and scintillator muon detectors 2.3 m below ground in the Cohiueco area

AUGER Engineering Radio Array: AERA

Detection of shower radio emission in the VHF band with an array of 160 (21 already installed) antennas on a 20 km² area close by Cohiueco


Enhancements and R&D Activities

Many R&D activities related to the detection of shower microwave emission: **AMBER, EASIER, FDWAVE, MIDAS**

New technologies for a novel tank design and a new telecommunication system for AUGER upgrades and/or a new giant UHECR detector

Cosmic ray event seen by the SD and EASIER

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Interdisciplinary activities and … Serendipity

Detection of an elve located at 80km altitude at a distance of 580km

Detection of a Forbush decrease seen by SD in “scaler mode”

Variation in the SD in “scaler mode” connected with the Feb 27 2010 Chile 8.8 magnitude earthquake
Energy Spectrum Measurement
- **Ankle position** \(10^{18.62}\) eV and **flux suppression** \(10^{19.4}\) eV measured with high accuracy using SD and hybrid data.

Arrival Direction
- **anisotropy** of the arrival direction of CR with \(E > 55\) EeV measured with a p-value of 33%. Directional search and large scale anisotropy studied.

Mass Composition
- The \(X_{\text{max}}\) and the RMS(\(X_{\text{max}}\)) vs E indicates a change from light to heavier composition for increasing E. Interpretation of results relies on hadronic models. Upper limits on photon fraction and neutrino fluxes.

Hadronic Interactions
Measurement of the **p-Air cross section** and estimate of the **p-p cross section at 57 TeV** in c.m.s. **Muon deficit** in model predictions compared to data.

Enhancements
HEAT and Infill allow lowering the energy threshold down to about \(10^{17}\) eV. **Muon detector** composition/hadint studies.

R&D activities
Test of new detection techniques (radio, microwave) are in progress.

Interdisciplinary science, ......