The Pierre Auger Observatory and its performance

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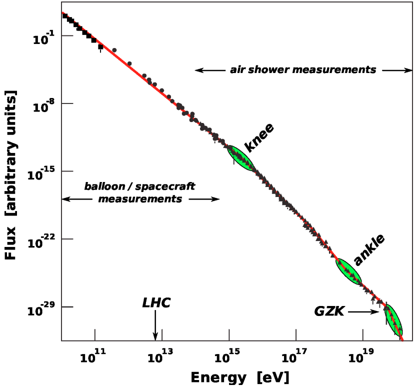
4th Workshop on Air Shower Detection at High Altitude

Physics motivations

Ultra High Energy Cosmic Rays (UHECR)

Measured spectrum extends to $E > 10^{20}$eV $\Rightarrow$ most energetic source of elementary particles available to scientists



- Messengers of the cosmos
  - Where and how are cosmic rays accelerated to these energies
  - No known astrophysical sources seem able to produce such enormous energies
  - Chemical composition unknown
- New particle physics
  - The high energy end of the spectrum probes physics at energies out of reach of any man made accelerator

Macroscopic energies, but very low flux !

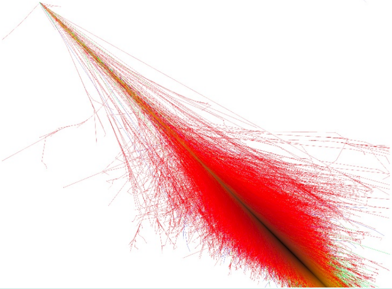
Above 100 EeV: less than 1 particle/km^2/century

Extensive Air Shower

UHECR study

Need to determine

- the cosmic ray energy
- the mass of the cosmic particles
- the particle arrival direction



Extensive air shower (EAS)

- Ultra high energy cosmic ray produces large shower of particles when entering in Earth's atmosphere (calorimeter)
- Cosmic particle characteristics obtained from the measured properties of extensive air showers

Pierre Auger Observatory

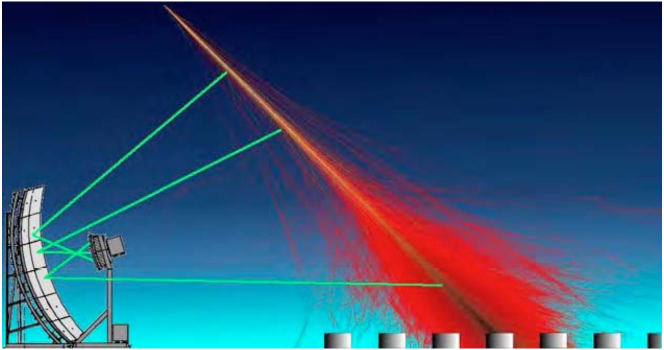
A cosmic ray observatory designed for a high statistics study of UHECR above 10^{18} eV by measuring the extensive air showers

EAS hybrid detection

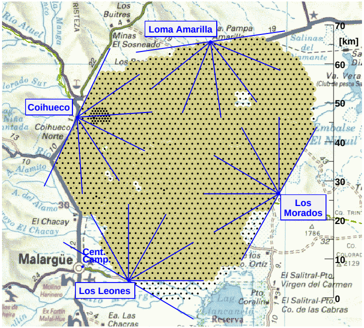
Key feature of the Pierre Auger Observatory

→ capability to measure:

- longitudinal development in atmosphere with fluorescence light telescopes
- lateral spread at ground level with ground based particle detectors



The largest cosmic ray detector in operation



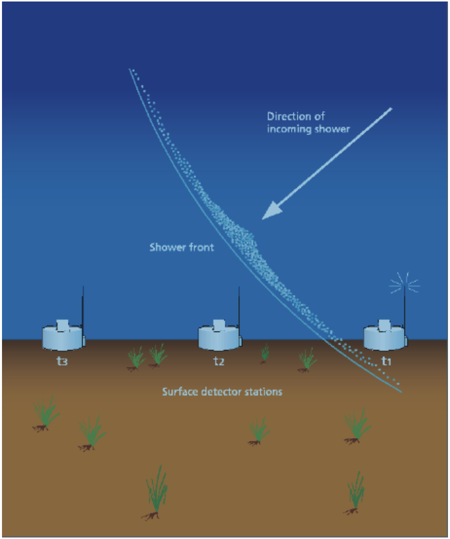
- 3000 km^2 in pampa Amarilla, Argentina
- surface detector (SD)
  - 1660 water Cherenkov detectors, triangular grid, 1500 m spacing
  - $\sim$ 100% duty cycle
  - $E_{threshold}$ at $\sim$ 3 EeV
- fluorescence detector (FD)
  - 24 +3 optical detectors in 4 buildings
  - $\sim$ 14% duty cycle
  - $E_{threshold} \lesssim 1$ EeV
- Data taking started in 2004, detector completed in 2008

The Pierre Auger Collaboration

- more than 500 collaborators
- 19 countries

The surface detector

Particle detection at ground

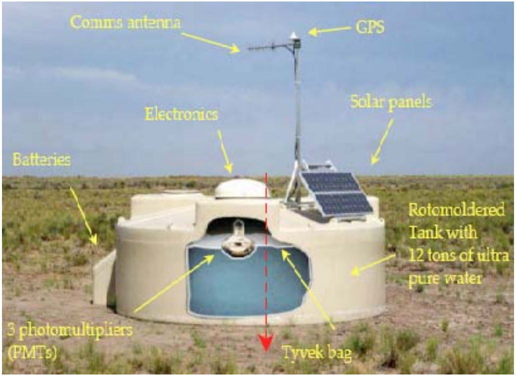


Event timing and direction

arrival times	shower angle
particle density	shower energy
muon number, rise time	measure of primary mass, interaction

The water Cherenkov detectors

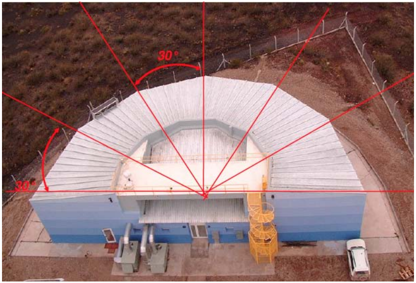
Detection of charged particles and γ

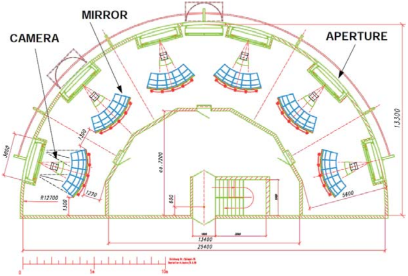


- 1 tank: 12 tons of pure water in a sealed liner with a reflective inner surface
- solar power system, providing 10 W
- three 9 inch PMTs, signals filtered and digitized in 25 ns bin, 10 bit FADC
- 2 shower triggers
- time stamp : GPS receiver
- trigger + signal information sent to the Central Data Acquisition System

The Fluorescence Detector (FD)

Fluorescence light emitted by nitrogen





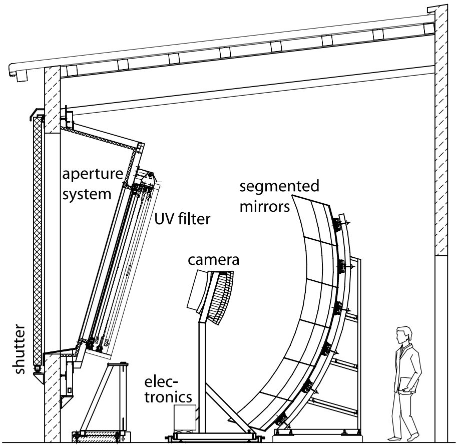
Fluorescence light proportional to the energy deposited by the shower

Ionization of nitrogen measured directly

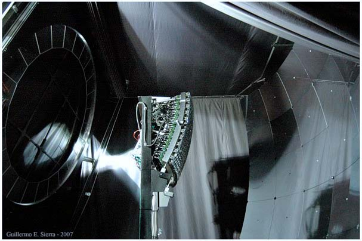
Calorimetric measurement	energy
Measurement of shower development, slant depth of shower maximum (X_{max})	mass composition

The fluorescence telescopes

UV light collection on a camera



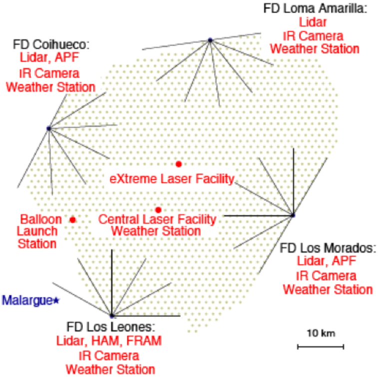
- Field of view : 30° in azimuth, 1.5 to 30° in elevation
- spherical mirror of 11 m^2
- corrector rings (lenses)
- camera with 20 x 22 pixels, 440 hexagonal PMTs
- pixel f.o.v $= 1.5^\circ \times 1.5^\circ$
- signal sampled at 100 MHz



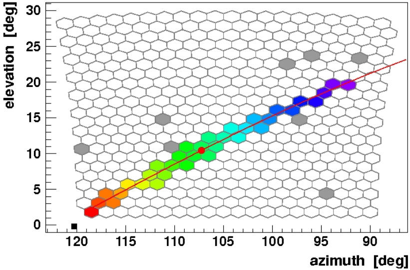
The atmosphere: calorimeter, scintillator, radiative transfer

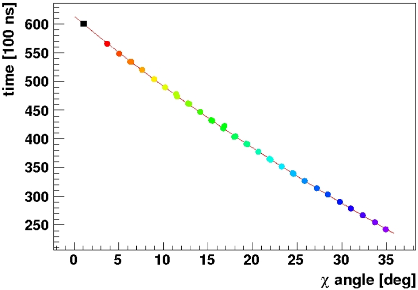
Light production (fluorescence, Cherenkov) and light transmission depending on atmospheric status.
To control the atmospheric conditions:

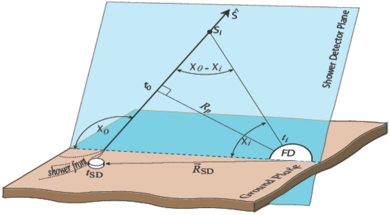
- five weather stations
- meteorological radio-sondes launched from a helium balloon station
- Aerosol monitoring
  - two central laser facilities
  - LIDAR
  - APF (Aerosol phase function monitor)
- cloud detection with IR cameras



Air shower reconstruction with the fluorescence detector





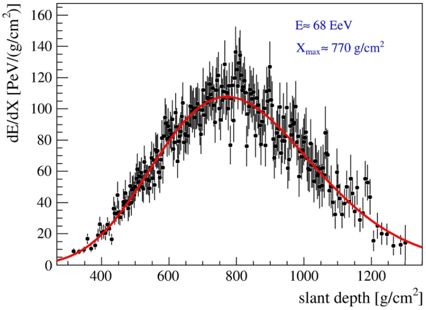


Shower geometry

- Shower Detector plane from direction of triggered pixels
- Timing information from the FD and the SD station with the largest signal
  $t_i = t_0 + \frac{R_p}{c} \tan\frac{(\pi - \chi_0 - \chi_i)}{2}$
- angular resolution $< 1^\circ$
- core position resolution $\sim$ 50m

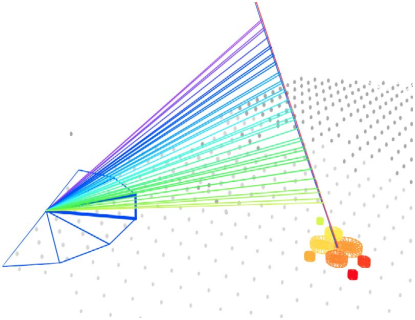
Calorimetric energy measurement

- Collected light converted in energy deposit as a function of traversed matter
  - calibrations of FD pixels
  - fluorescence and Cherenkov light
  - attenuation, multiple scattering
  - fluorescence yield dependence on T, P and humidity

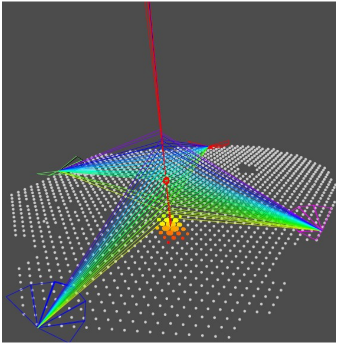


- Longitudinal shower profile: Gaisser-Hillas function
- Energy of the cosmic ray
  - integral over the entire longitudinal profile
  - correction for E_{inv} carried away by ν and high energy μ ($\sim$ 9%)
- FD energy resolution $\sim$ 7.6% (constant with energy)

Hybrid Event



4-fold Hybrid Event



shower viewed in stereo (observed by more than 1 FD site)

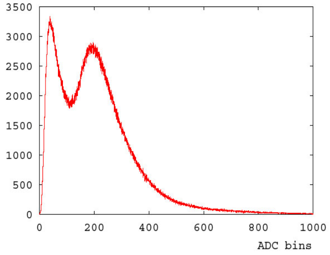
- at 10^{19} eV, over 60%
- at 3×10^{19}, over 90%

Independant hybrid reconstructions ⇒ cross-checks.
Confirms resolution of 20 g/cm^2 on X_{max}

Air shower reconstruction with the surface detector

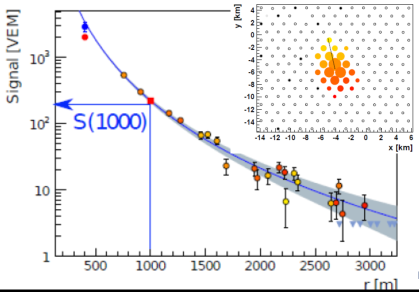
Cerenkov Detector calibration

- Signals converted in VEM = total charge deposited by a vertical muon crossing the center of the tank.
- Common reference level between tanks
- Determination of the VEM unit with background muons.
- Calibration performed continuously.



Shower geometry and lateral distribution

- shower axis from particle arrival time angular resolution $< 1^\circ$ if $N_{\mathrm{tank}} \geq 6$
- impact point and lateral distribution from a global likelihood
- fluctuations of the LDF minimized at 1000m



S(1000), signal at 1000m, reconstruction accuracy

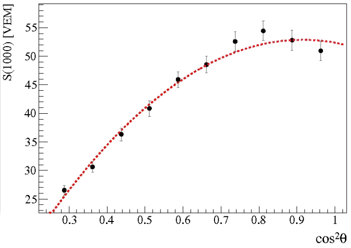
Composed by 3 contributions:

- statistical uncertainty due to the finite size of the detector and the limited dynamic range of the signal detection,
- systematic uncertainty due to the assumptions of the shape of the lateral distribution
- systematic uncertainty due to the shower-to-shower fluctuations

relative uncertainty $\sim 14\%$.

SD Energy estimator

- Constant Intensity Cut (CIC) method to correct for the attenuation based on data $\Rightarrow$ no resort to simulation
- $S_{38} = \frac{S(1000)}{CIC(\theta)}$

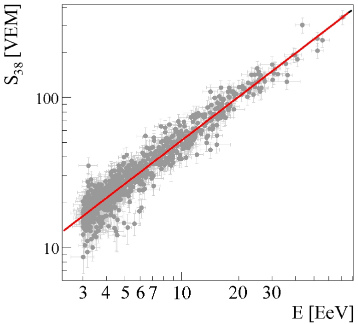


Calibration of the SD energy estimator: with hybrid events

Energy calibration

Aim: relate the SD energy estimator to the FD energy measurement

- Subset of high quality hybrid events
- Energy estimator from these events reconstructed by the SD and the FD
- 839 selected hybrid events with $E_{FD} \geq 3$EeV
- relation between S_{38} and E_{FD} described by: $E_{FD} = A\ S_{38}^{B}$



Hybrid concept

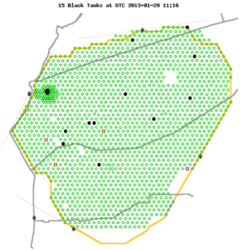
- ⇒ calibration method independent of MC simulation
- Systematics uncertainty: 7% at 10 EeV, 15% at 100 EeV

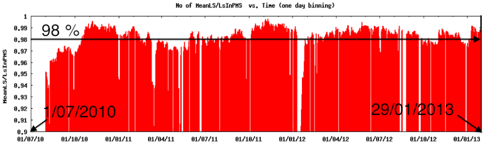
Systematics on FD energy scale

fluorescence yield	14 %
FD absolute calibration	9.5 %
reconstruction procedure	10 %
atmospheric effects	8 %
invisible energy	4 %

Observatory Performance

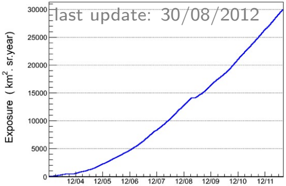
SD efficiency (monitoring web site)





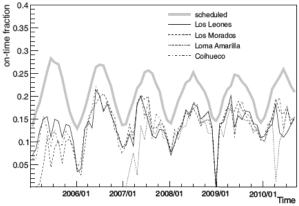
SD Exposure

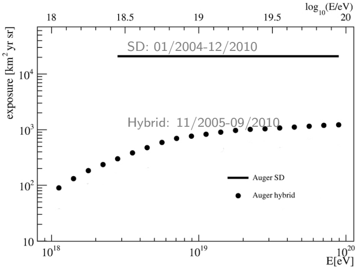
- geometrical calculation counting active hexagons.
- not relying on simulations
- above 3 EeV, array fully efficient
- independent of primary mass
- systematic uncertainty: $\sim 3\%$



Observatory Performance

FD on-time





Hybrid Exposure

average duty cycle ($\sim$ 14%)

- time-dependent Monte Carlo simulations (actual data taking conditions)
- syst. uncertainties $\sim$ 10% (6%) at 10^{18} eV (10^{19} eV)

up to 31/12/2012

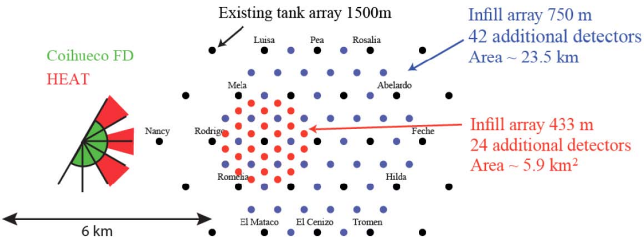
- $\sim$ 31400 km^2 sr year
- more than 58000 events above 3 EeV, more than 7200 above 10 EeV

Major breakthroughs and results in the field of UHECR

$\Rightarrow$ **Lorenzo Perrone's talk**

Extension towards the lower energies

- Improve detector performance between $\sim 10^{17}$ and 10^{18} eV



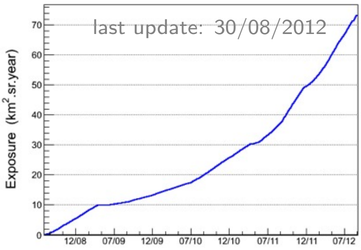
HEAT

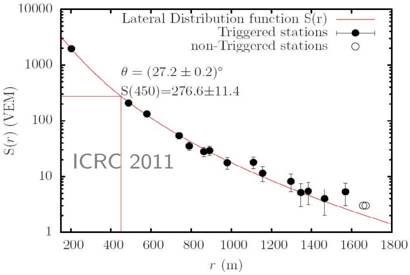
- 3 telescopes with higher elevation 30° up to 60°
- Taking data since Sept. 2009

Enhancements

AMIGA

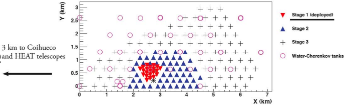
- Infill array with water Cherenkov stations
- Muon detectors with buried scintillators





Auger Engineering Radio Array (AERA)

- Observation of radio emission from electromagnetic cascade in 10-100 MHz
- Emission mechanism due to the deflection of e^+, e^- in the Earth's magnetic field (dominant) and to charge excess
- Technical challenge: develop a large-scale autonomous antenna array, triggering directly on the radio pulses.



R& D on micro wave detection

- Bremsstrahlung emission in microwave regime, unpolarized and isotropic

- nearly 100% duty cycle, negligible atmospheric absorption
- prototypes on Auger Observatory site :
  - Parabolic dish reflector, instrumented with an array of antenna horns
  - Feed horns located on particle detectors

Conclusions

Pierre Auger Observatory

- Hybrid detection: FD provides nearly calorimetric energy measurement, SD huge aperture easily calculable, FD calibrates SD energy scale
- Minimal use of simulations in the production of key scientific outputs
- Complementary detection systems, to lower the energy threshold of the baseline detectors from 1 EeV to 0.1 EeV
- Hybrid detection and high statistics $\Rightarrow$ valuable performances to measure the extended air showers with unprecedented precision
  Next talk by Lorenzo Perrone

Future of the Observatory and more

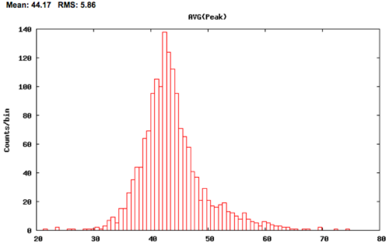
Goal: identify the primary cosmic ray nature

- upgrade of the surface detector: frontend electronics going to faster sampling (120 MHz)
- modified water Cherenkov liners to have faster time response and better separate the electromagnetic and the muon components
- add supplementary muon detectors

Thank you for your attention

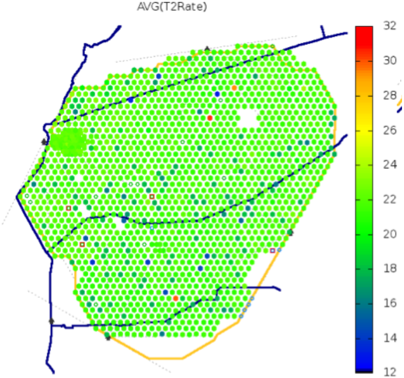
Uniform behaviour of the whole array

Averaged value (per LS) of PMT monitoring data for the whole array

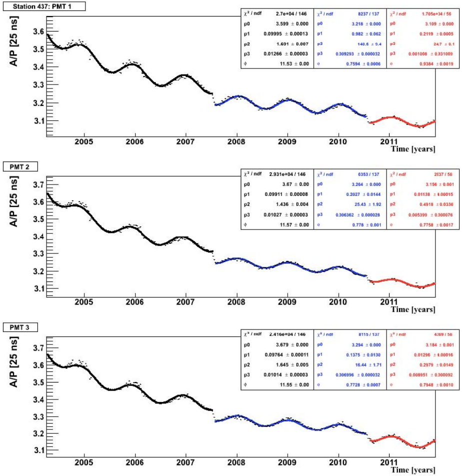


Draw Monitoring Data For The Whole Array

Station



Long term behaviour



Aera/Peak (correlated with signal decay constant)

- A slight global decrease
- Small seasonal variations
- Continuous calibration takes into account signal variations
- Expected fractional signal loss in 10 years $<10\% \Rightarrow$ confidence in a very stable long term performance.