Tenth Journal Club: «A Catalog of the Highest-Energy Cosmic Rays Recorded During Phase I of Operation of the Pierre Auger Observatory

Corso di Astrofisica Nucleare e Subnucleare

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https://arxiv.org/pdf/2211.16020.pdf

Abstract

ABSTRACT

A catalog containing details of the highest-energy cosmic rays recorded through the detection of extensive air-showers at the Pierre Auger Observatory is presented with the aim of opening the data to detailed examination. Descriptions of the 100 showers created by the highest-energy particles recorded between 1 January 2004 and 31 December 2020 are given for cosmic rays that have energies in the range 78 EeV to 166 EeV. Details are also given of a further nine very-energetic events that have been used in the calibration procedure adopted to determine the energy of each primary. A sky plot of the arrival directions of the most energetic particles is shown. No interpretations of the data are offered.

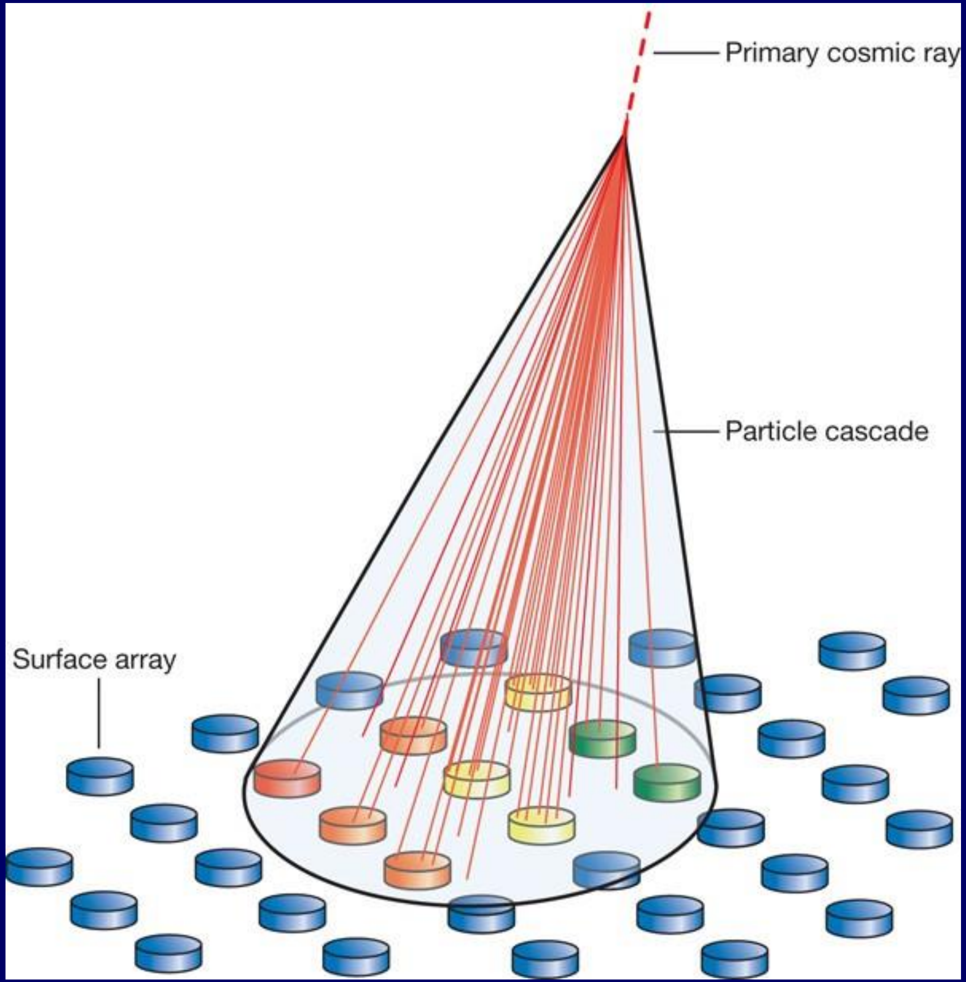
What the observatory is looking for

- Looking for Ultra High Energy Cosmic Rays

  $(> 1\,EeV = 10^{18}\,eV)$

- The flux above 50 EeV is about $0.5\,particles\,km^{-2}\,century^{-1}$ → can't use satellites/balloons & need to study air showers

- Air showers at that energy reach the ground in a surface that is $\sim 10 - 50\,km^2$ → need large collecting area.

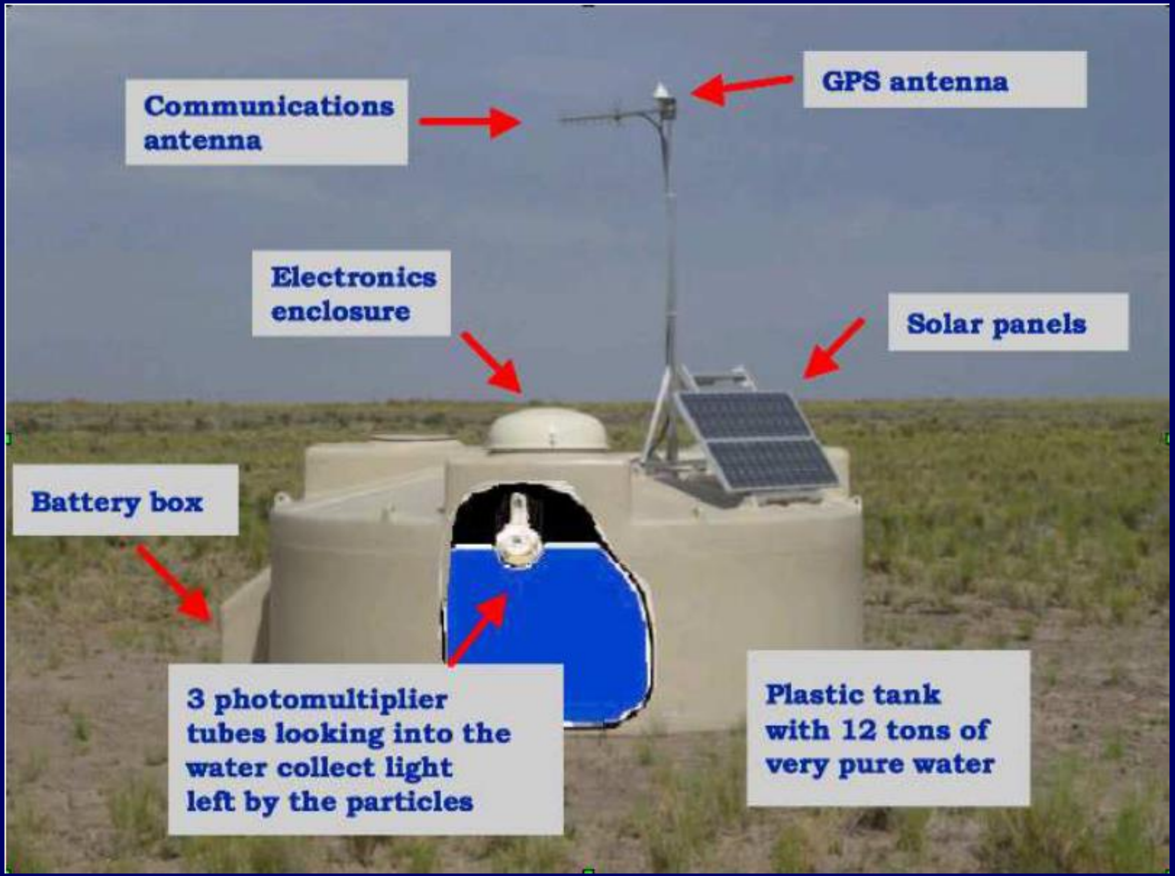


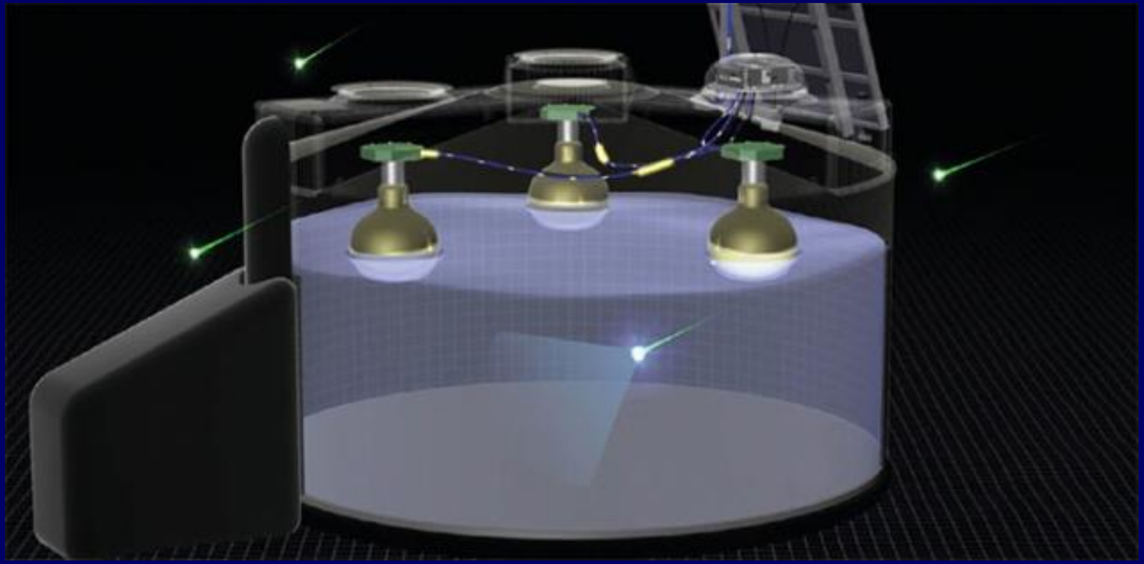
How to detect high energy cosmic rays

- Need to look for cascades: try to detect particles that reach the ground or visible radiation that is produced when particles travel in the atmosphere
- If primary particle is proton/ion then first interaction produces $\sim 100s$ of $\pi^0, \pi^\pm$
- $\pi^0 \rightarrow \gamma\gamma \rightarrow$ electromagnetic shower
- While $\pi^\pm$ form hadronic showers (mainly other pions) until their energy reaches $\sim 300\ GeV$, afterwards they decay mostly $\pi^\pm \rightarrow \mu^\pm \nu_\mu$
- Final state radiation is composed mainly by $\gamma, e^\pm, \mu^\pm$
- Cherenkov detectors are used (also scintillators in AugerPrime)

How to detect high energy cosmic rays

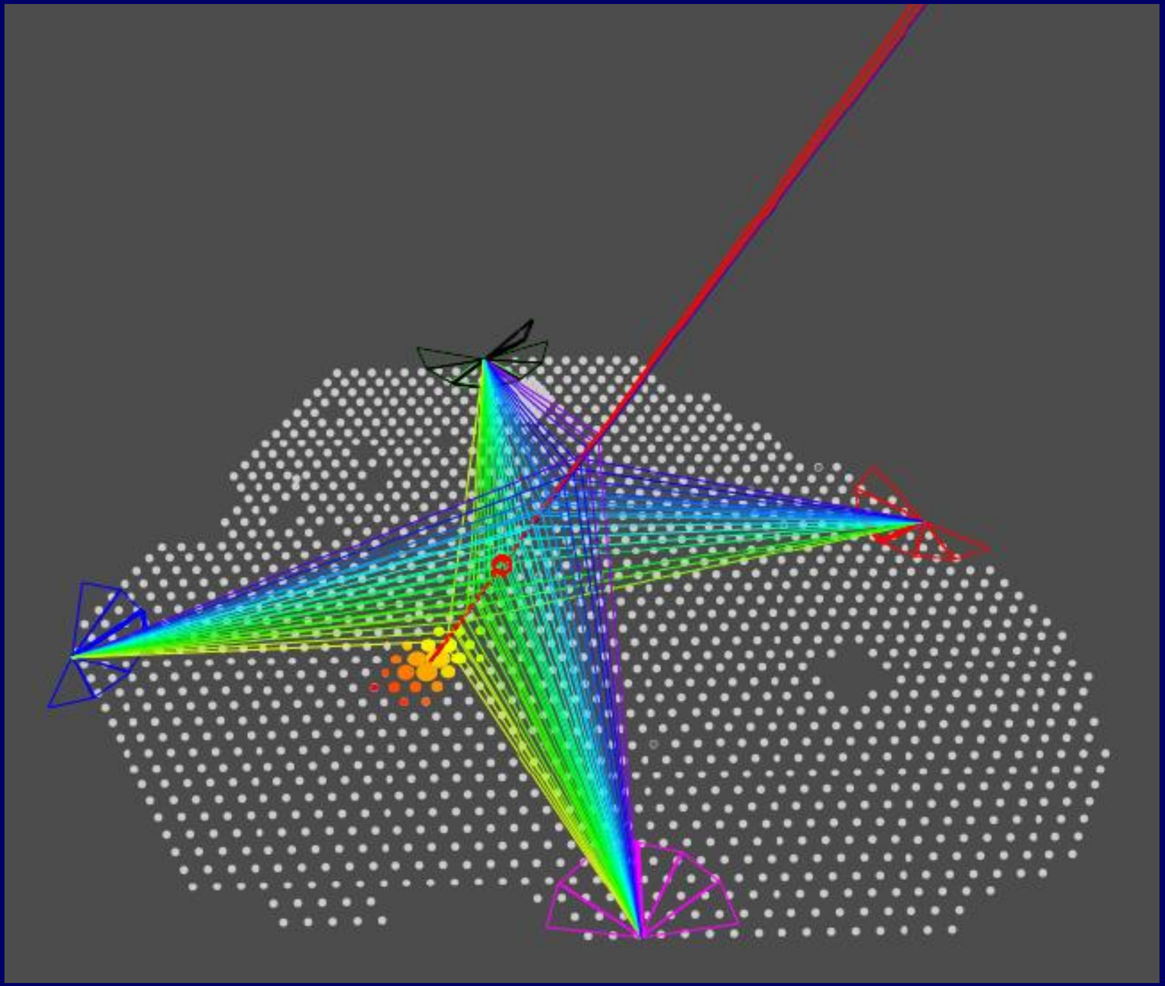
The Water Cherenkov Detectors





How to detect high energy cosmic rays

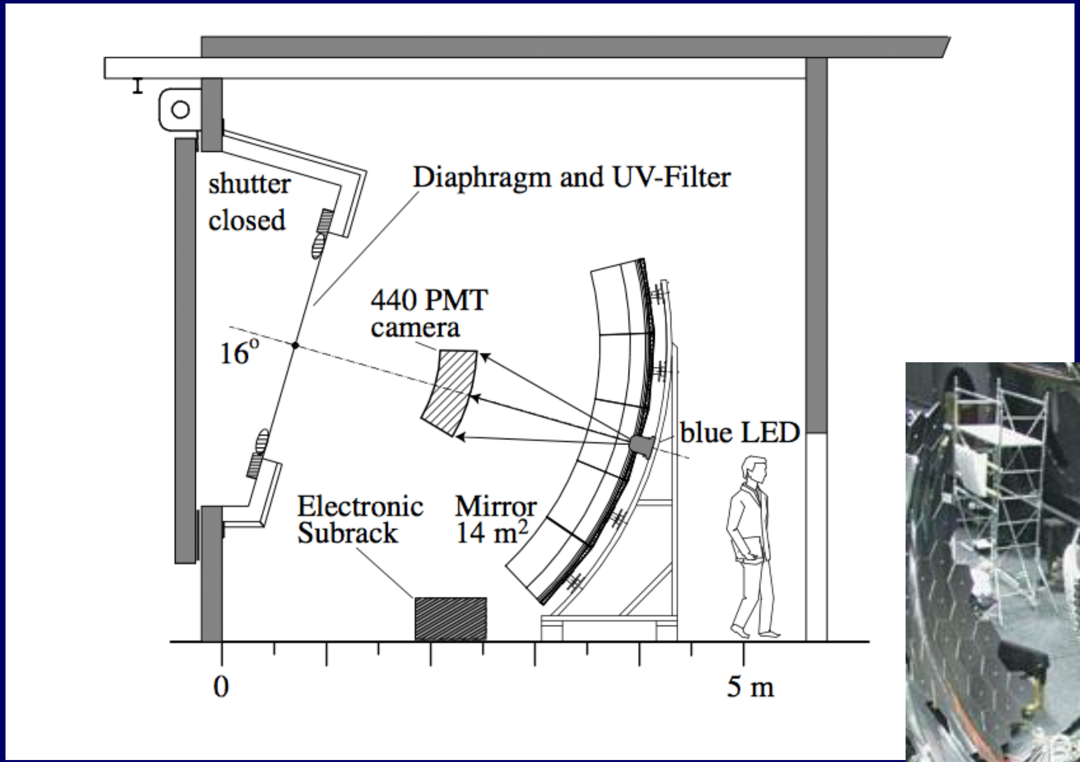
- Charged particles of the shower can also excitate (mainly) the nitrogen atoms in the atmosphere
- Very faint source: 5.6 γ for every MeV of ionization in the range $300 \div 400\, nm$, but isotropic.
- Charged particles can also emit Cherenkov radiation in the atmosphere
- Brighter: 30 γ per meter of track in the range $400 \div 700\, nm$, but only at a small angle with respect to the direction of motion of the particle

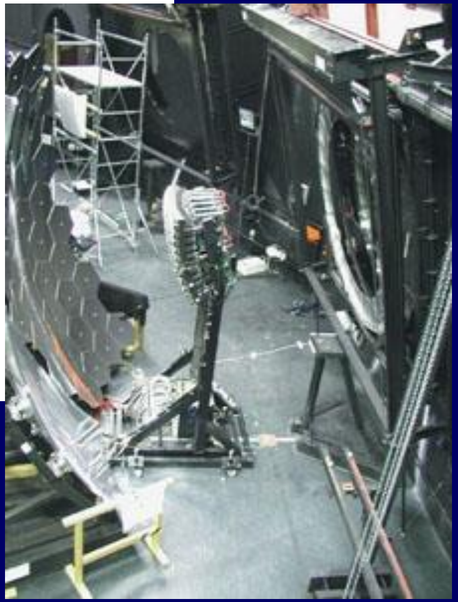


How to detect high energy cosmic rays

Fluorescence detectors

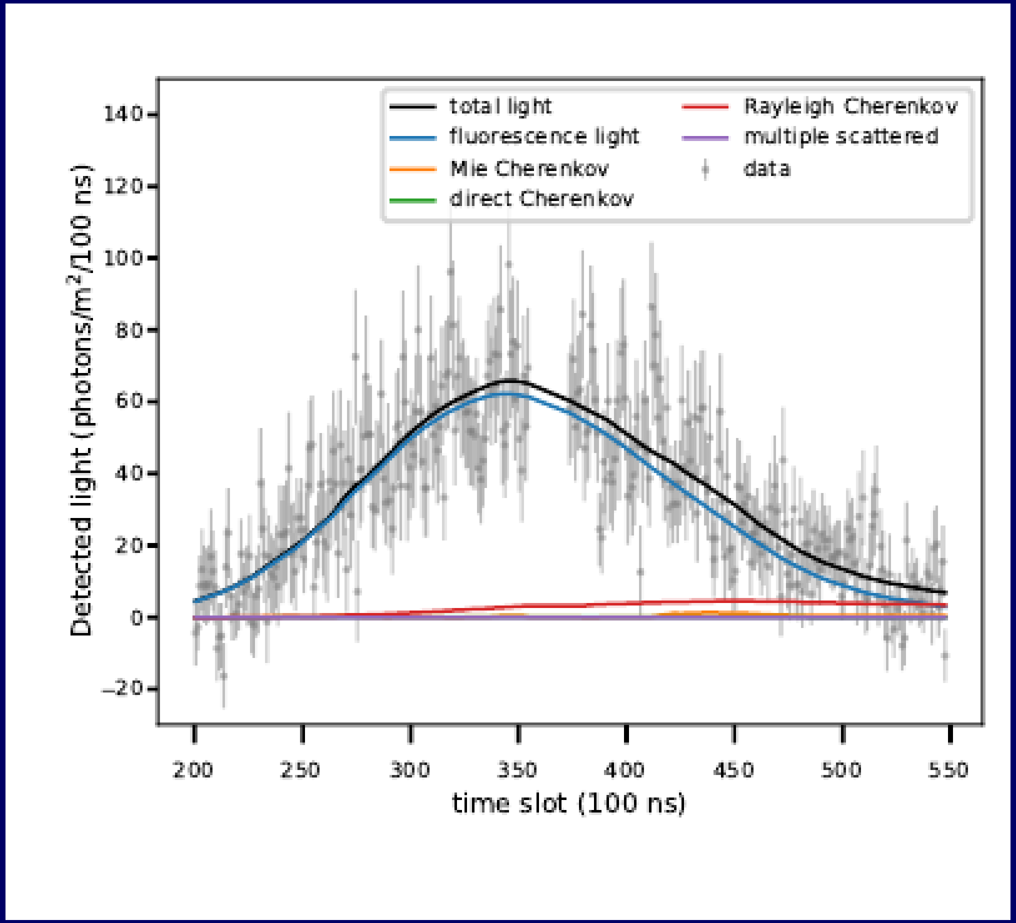
- Essential to do a calorimetric measurement of the primary particle energy and improves direction estimation
- 4 fluorescence detectors at different ends of the observatory
- 30° azimuthal field of view
- 29° maximum elevation





How to detect high energy cosmic rays

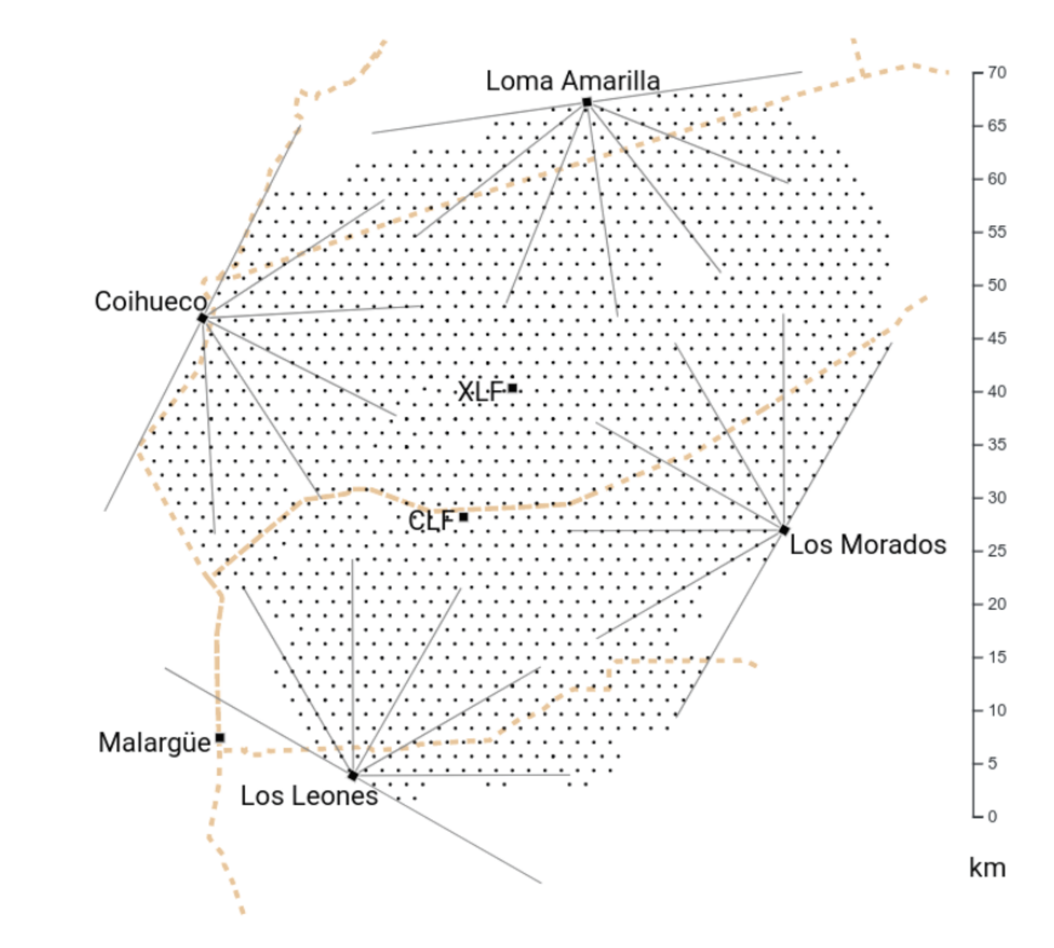
Fluorescence detectors



Light flux profile for the event PAO140131

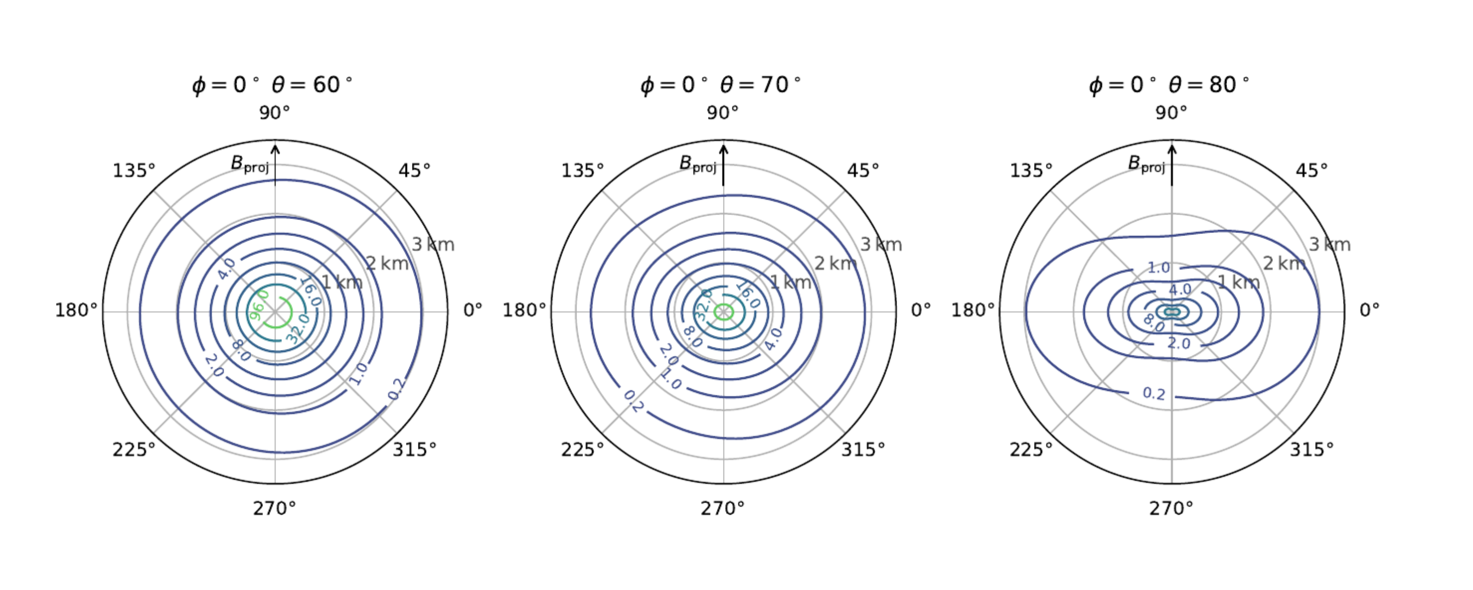
The observatory

- 1600 Water Cherenkov Detectors
- Trigger when coincidence of at least 3 of them
- 4 Fluoresecence Detectors
- 3000 km^2 area
- XLF, CLF steerable lasers to monitor atmospheric conditions
- Located in Western Argentina
- Altitude of 1400 m
- Collaboration of 500 scientists from 15 countries



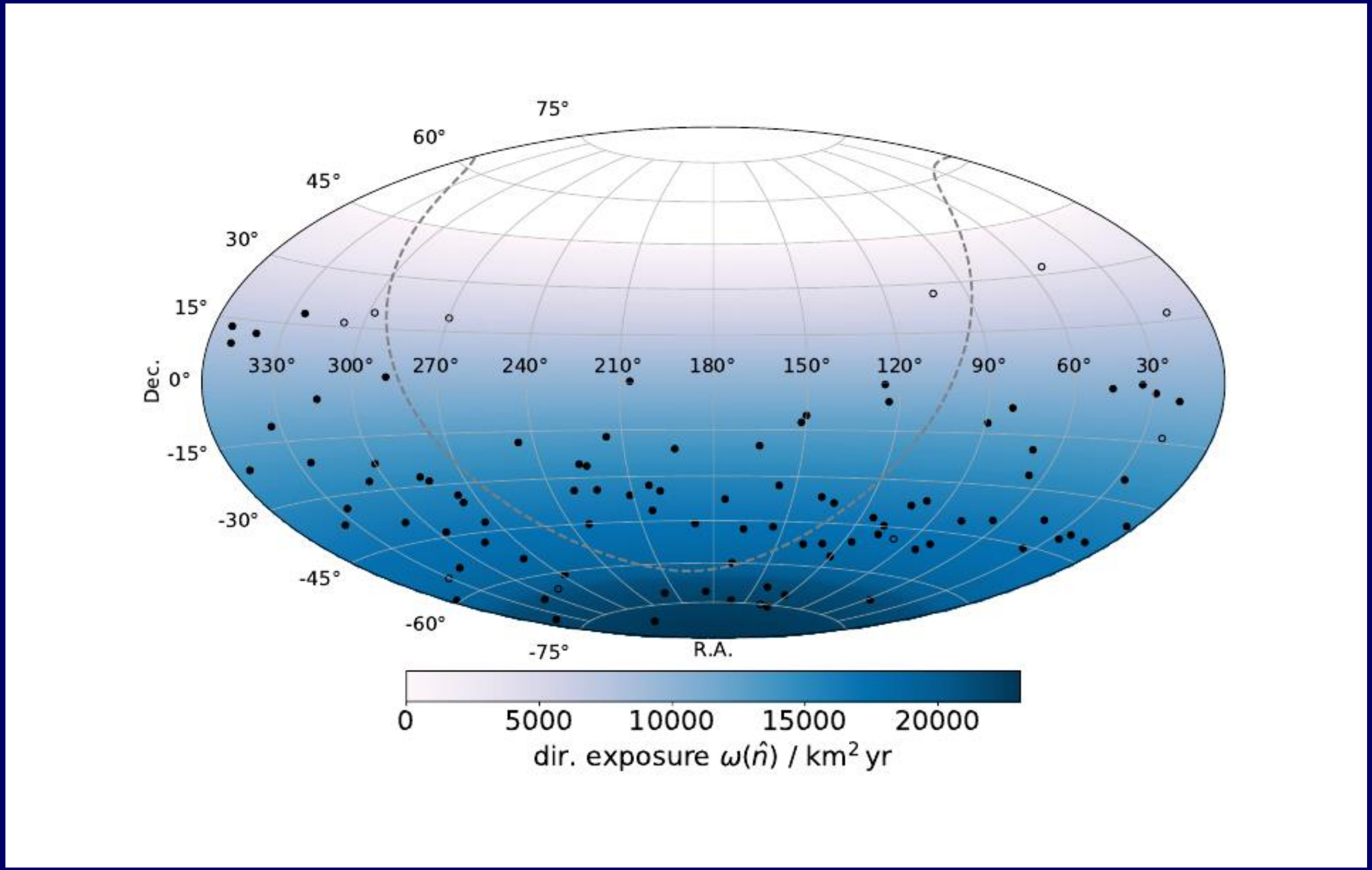
Reconstruction of the event

- Inclination found by timing of vertical signals ($\theta < 60°$) and by studying distribution of the muon density for horizontal signals ($\theta > 60°$).
- More precision obtained with the hybrid data: by using also the fluorescent detectors, but they only work at night & with clear skies. Precision ~ 0.6 °, can reach ~ 0.4 ° for very energetic events
- Energy of primary found by integrating energy deposit seen by the fluorescence detectors and by fitting lateral profile seen by the WCD. Uncertainty of ~ 14%.



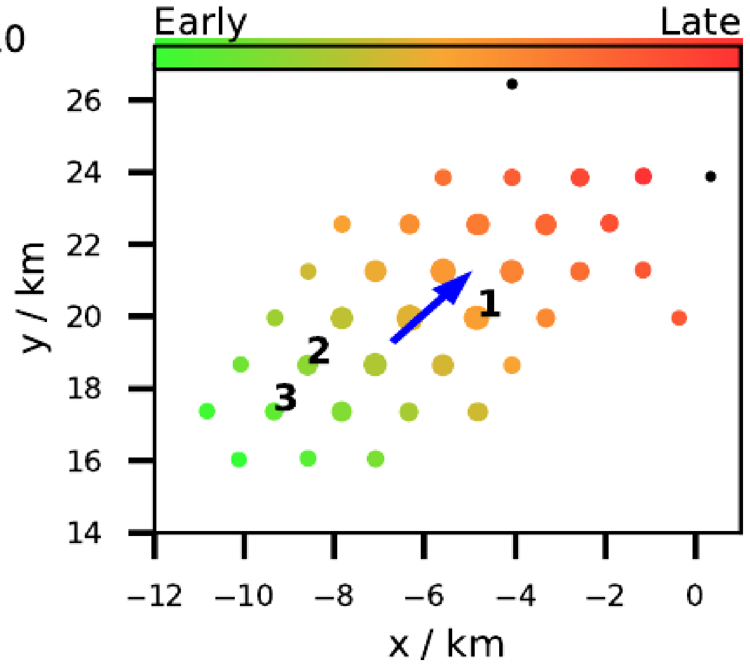
Plots of muon density for E=10 EeV.

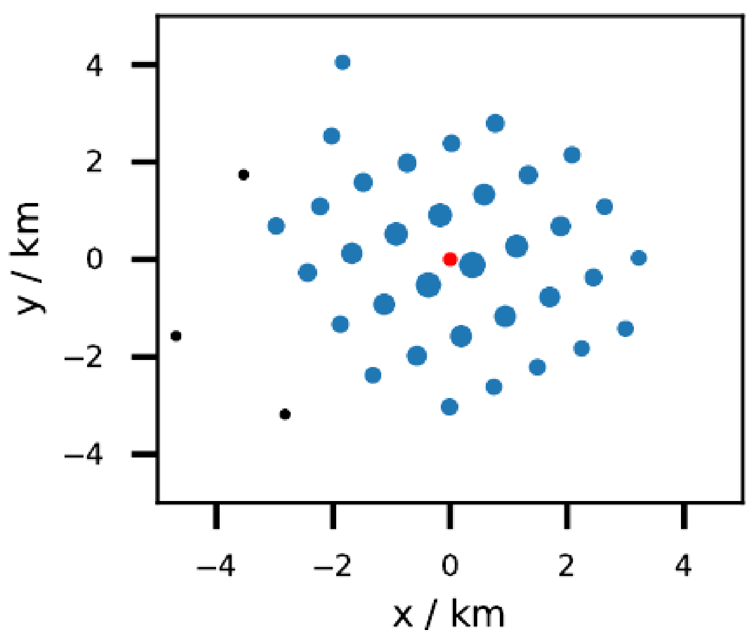
The 100 highest energy events



An example of an event recorded at the Auger Observatory: PAO191110

Date	2019-11-10
Energy [EeV]	166±13
θ [deg]	58.6
ϕ [deg]	224.4
α [deg]	128.9
δ [deg]	-52.0
β	-2.0
$t_{1/2}(1000)$ [ns]	98±3
Multiplicity	34

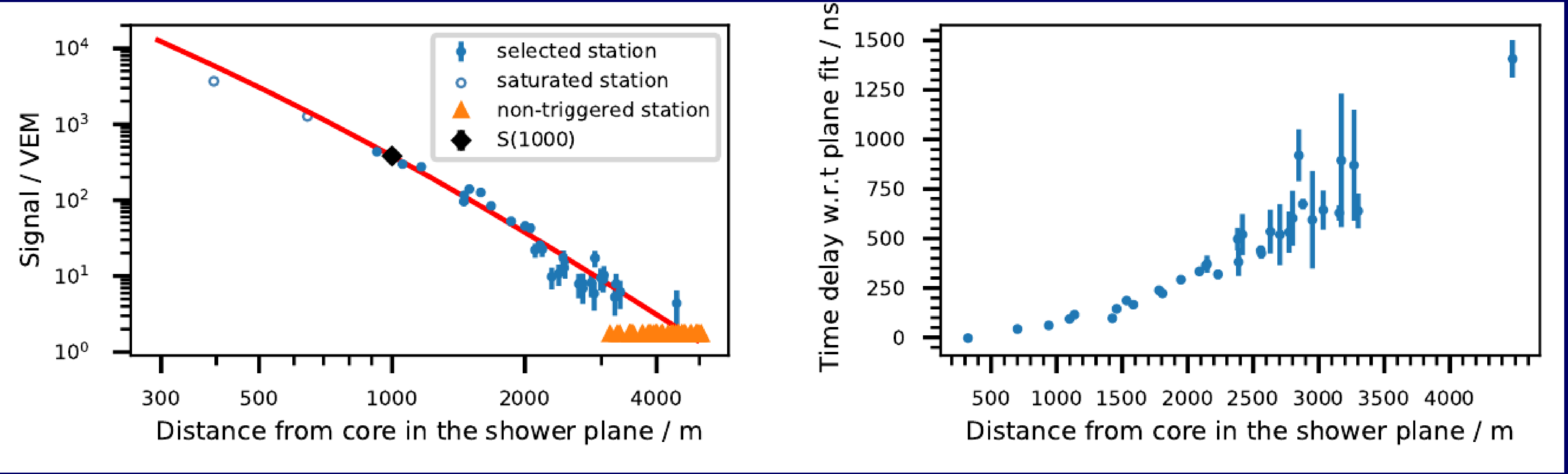




Auger Catalog

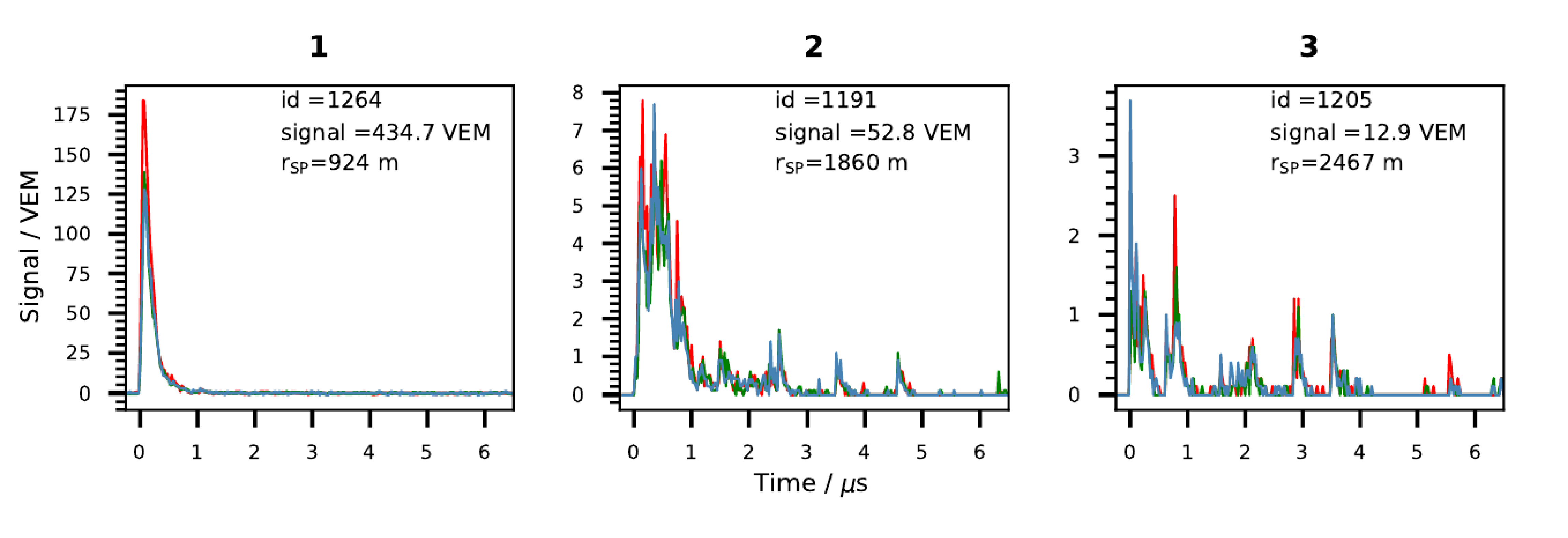
Detectors that emitted a signal related to the event (34 in this case). Black ones had noise signal. Blue arrow indicates direction of shower. Color grading indicates timing. Radius of each cirle is proportional to logarithm of energy deposition.

An example of an event recorded at the Auger Observatory: PAO191110



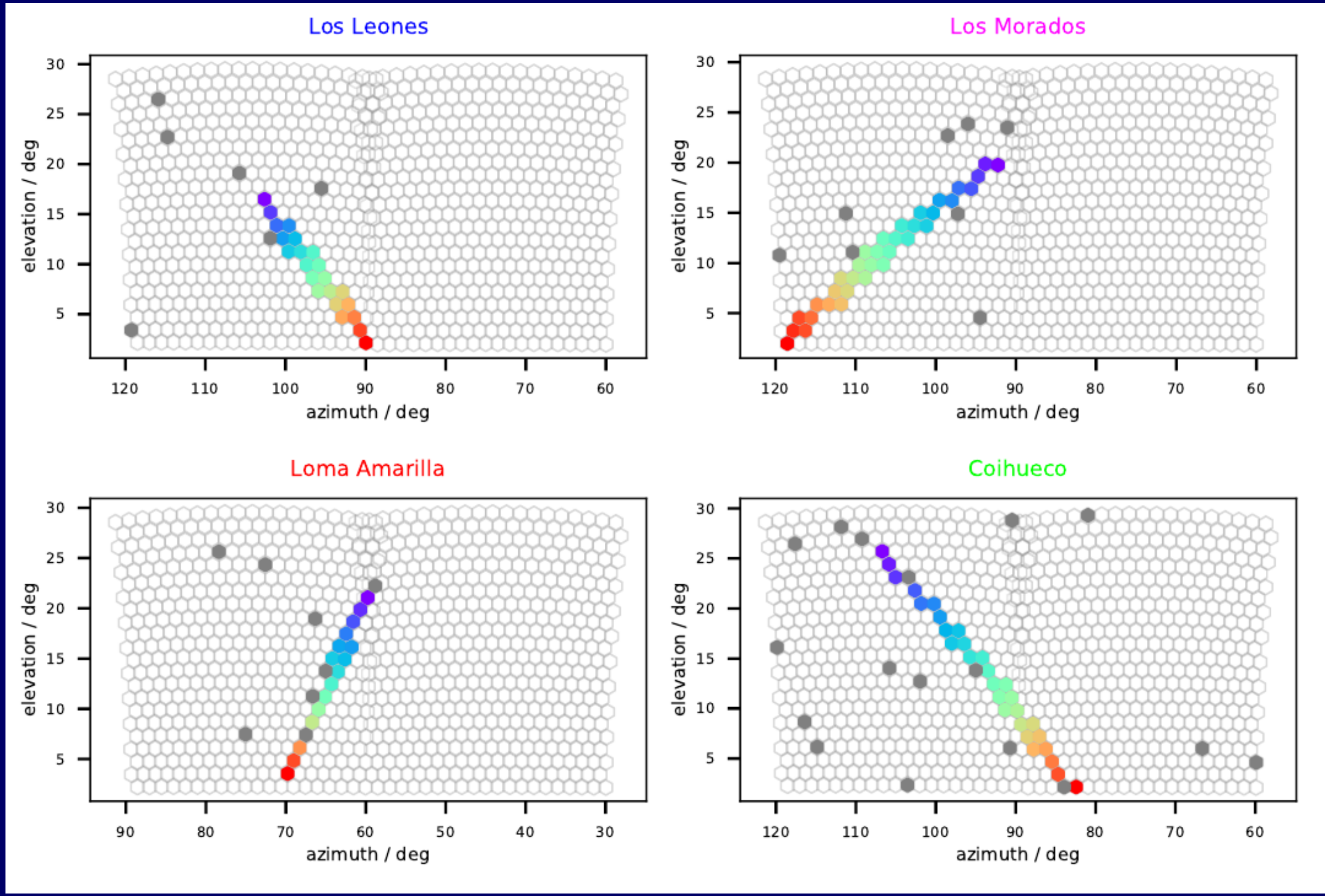
The signal and time delay with respect to the distance of the axis of the shower. Distances measured in the shower plane. VEM «Vertical Equivalent Muons», means the mean energy deposit of a minimum ioninizing muon in a water cherenkov detector ($\sim 250\ MeV$).

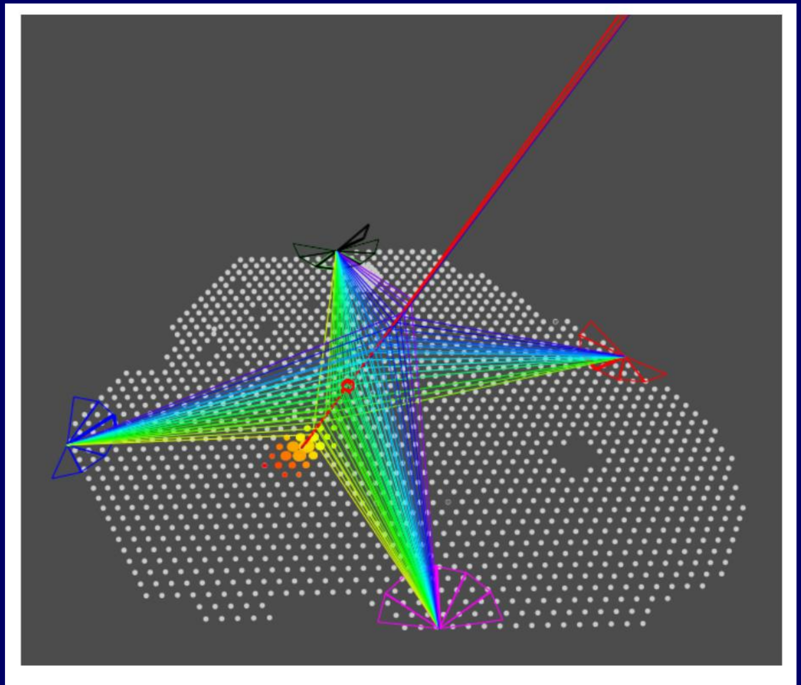
An example of an event recorded at the Auger Observatory: PAO191110



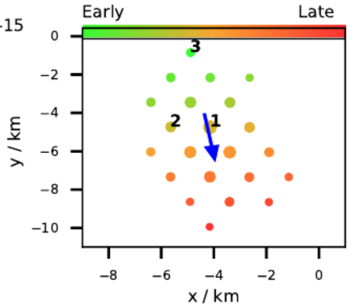
The readings of the PMTs at 3 different detectors (indicated 2 slides before). Except within a few meters of the shower axis, muons precede the electromagnetic component. The electromagnetic component lags the muon signals by an amount that increases with distance from the shower core.

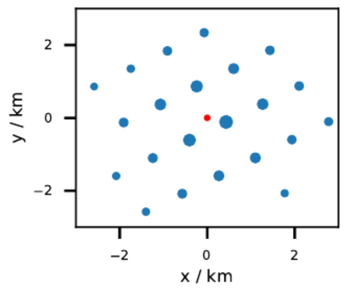
PAO100815: an hybrid event





Date	2010-08-15
Energy [EeV]	82±7
θ [deg]	53.8
ϕ [deg]	100.6
α [deg]	324.5
δ [deg]	17.8
β	-2.1
$t_{1/2}(1000)$ [ns]	127±5
Multiplicity	22





Thanks for the attention