Identification of Cosmic Rays: searches of UHE neutrinos, photons and nuclear elements at the Pierre Auger Observatory

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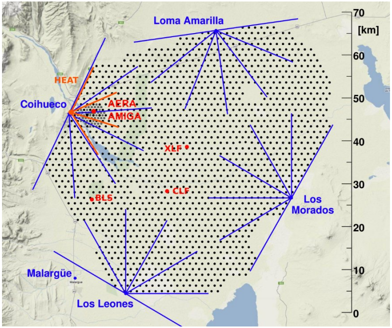
Outline

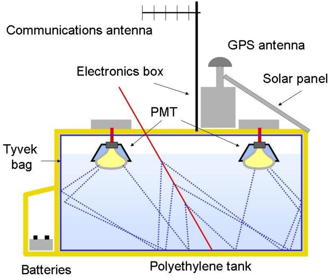
References for the Pierre Auger Collaboration
(Most recent) Contributions to ICRC 2013 arXiv:1307.5059
(Full paper list) www.auger.org

Pierre Auger Observatory



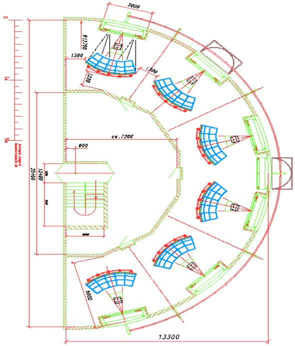
- Located at Malargue, Mendoza, Argentina
- Hybrid design, completed in March 2008, in data taking since 2004
- Surface Detector (SD): 1660 water Cherenkov tanks in a triangular grid with 1.5 Km spacing - 3000 km^2
- Fluorescence Detector (FD): 24+3 Telescopes in 4+1 sites
- Atmospheric monitoring: 4 Lidar stations, Central Laser Facility (CLF), weather stations, balloons, IR cloud cameras
- High elevation telescopes (HEAT), SD array with finer granularity, muon counters (AMIGA), radio antennas (AERA),...

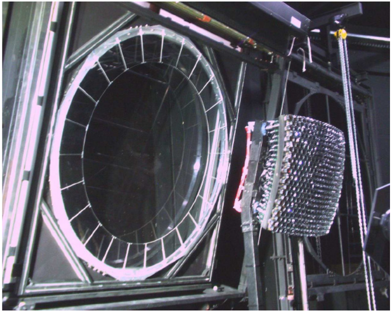
Surface Detector (SD)



- 12 tonnes of ultra puer water
- 3 Photonis PMTs (diameter 12 cm)
- FADC sampling rate 40 MHz
- Solar panels for power supply
- Time tagging with GPS system (8 ns resolution),antenna for data transfer
- Signal calibration in Vertical Equivalent Muons (VEMs)

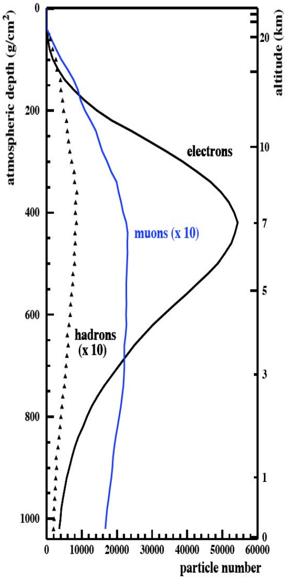
Fluorescence Detector (FD)

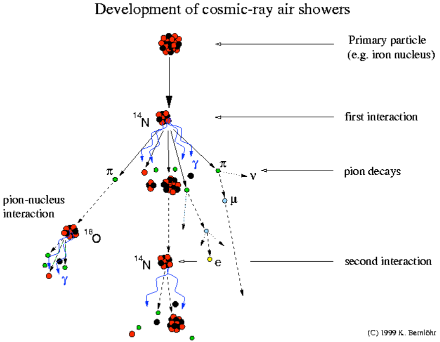




- 6 telescopes/FD site
- Telescope aperture: 30^ox30^o
- Camera: 22x20 Photonis PMTs
- FADC sampling rate: 10 MHz
- Time tagging with GPS system
- Absolute and relative calibration (UV LED)
- Atmosphere calibrated with many devices (Lidar, CLF, radio soundings, . . .)

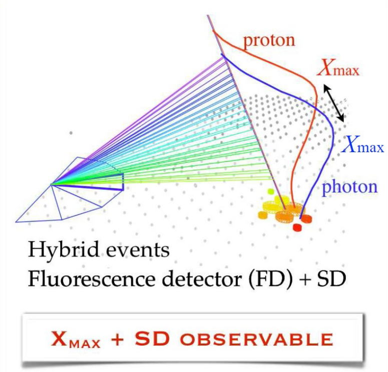
Characteristics of particle shower

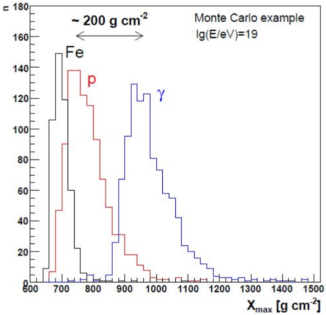




- Decay of neutral pions feeds em. shower component
- Decay of charged pions feeds muonic component
- Superposition and semi-superposition models applicable to inclusive (averaged) observables
- Showers from heavy nuclei will develop higher, faster, with less shower to shower fluctuations and with higher muon content than lighter nuclei showers.

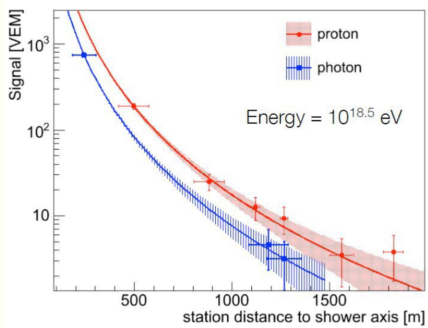
Photon - hadron discrimination





Photons develop deeper in atmosphere and fluctuate more than proton and iron

Photon - hadron discrimination

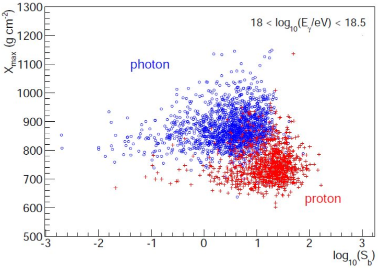


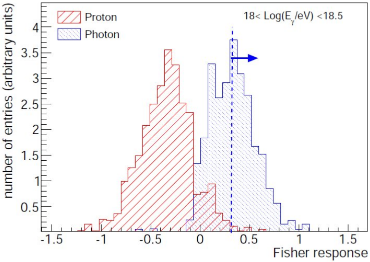
- Smaller signals (due to smaller muon content)
- Fewer trigger stations
- Sharper lateral distribution

$$S_b = \sum_i S_i \left(\frac{R_i}{R_{ref}} \right)^b$$

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

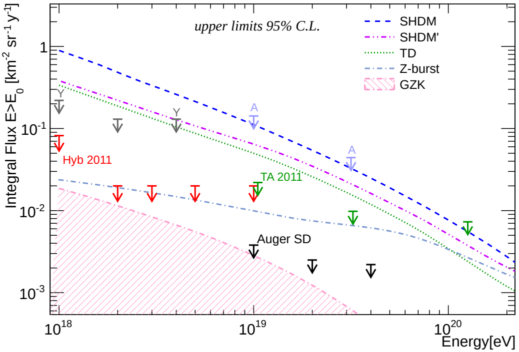
Photon selection





- Fisher Analysis
  - $F = w_1.x_1 + w_2.x_2$
- Photon efficiency 50%
- Proton contamination $<$ 1 %

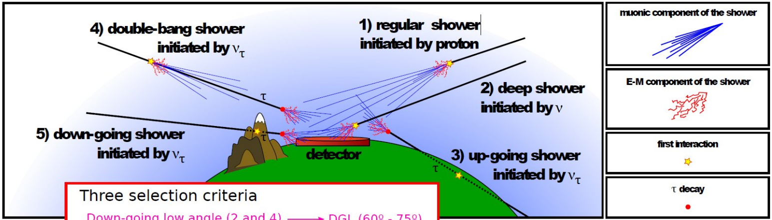
Photon limits



- No candidates over the expected background
- Top Down models disfavored
- GZK region ($p + \gamma_{CMB} \rightarrow p + \pi^0(\rightarrow \gamma\gamma)$) within reach in the next few years

Neutrino identification

- The discrimination power is enhanced when looking at inclined showers $\rightarrow$ large slant depth.
- Neutrinos identified as inclined young (deep) shower
- (1) Nucleonic cosmic rays initiate showers high in the atmosphere.
- Shower at ground: narrow front mainly composed of muons (electromagnetic component absorbed in atmosphere).
- (2-5) Neutrinos can initiate deep showers
- Shower at ground: broad front with electromagnetic + muonic components

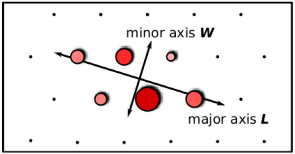


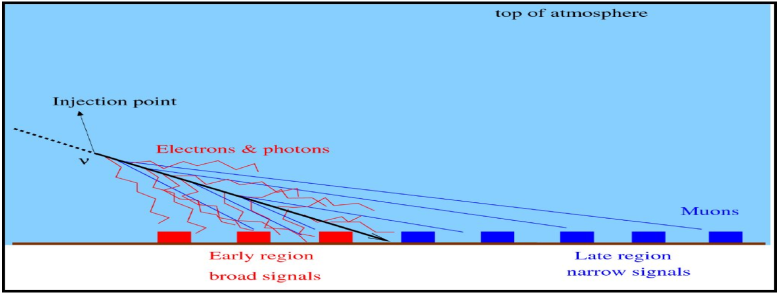
Three selection criteria

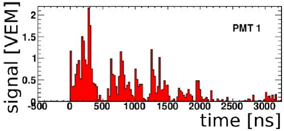
Down-going low angle (2 and 4) ⟶ DGL (60º - 75º)
Down-going high angle (2, 4 and 5) ⟶ DGH (75º - 90º)
Earth-skimming (3) ⟶ ES (90º - 95º)

Neutrino identification

- Elongated footprint



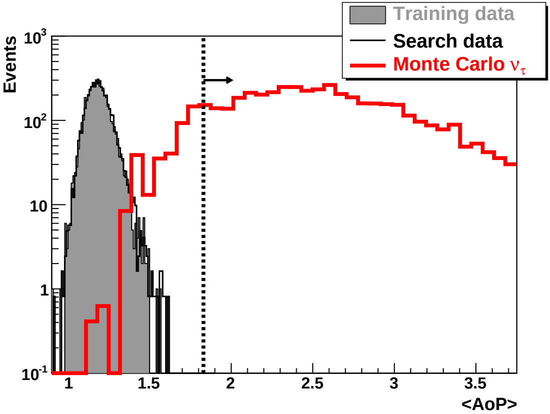




- Broad signals in time induced in the early region
- Larger Area over Peak ratios

Neutrino selection for Earth-Skimming analysis

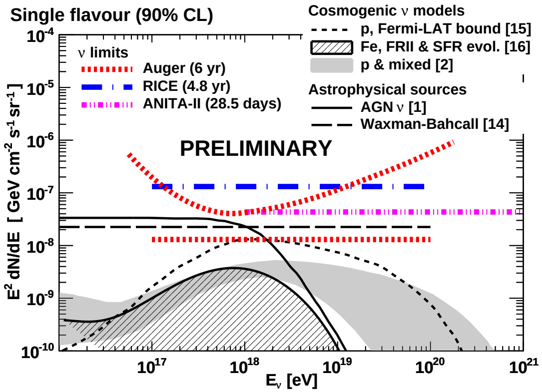
- Training Sample 20% of data
- Neutrino simulation in all parameter space



- neutrino candidate if $< AoP >$ greater than 1.83
- Cut placed at 1 expected event in 50 yr
- Selection efficiency 90%

Neutrino limits

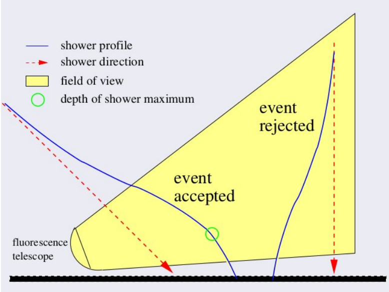
- No candidates found
- Competitive limit to UHE neutrino flux
- Good sensitivity in the GZK expected region ($p + \gamma_{CMB} \rightarrow n + \pi^+(\rightarrow \mu^+\nu)$)

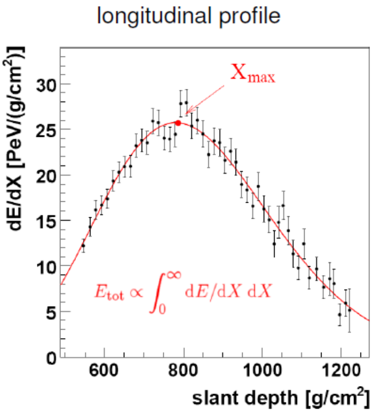


Nuclear mass

- Information on the shower development can be extracted using both the SD and the FD of the Pierre Auger Observatory
- From the Fluorescence Detector:
  - X_{max}
  - RMS(X_{max})
- From the Surface Detector:
  - Depth profile of muon production:
    X^{μ}_{max} the depth along the shower axis where the number of produced muons reaches a maximum
  - Independent from X_{max} and can go to higher energies

Longitudinal development: $X_{\max}$

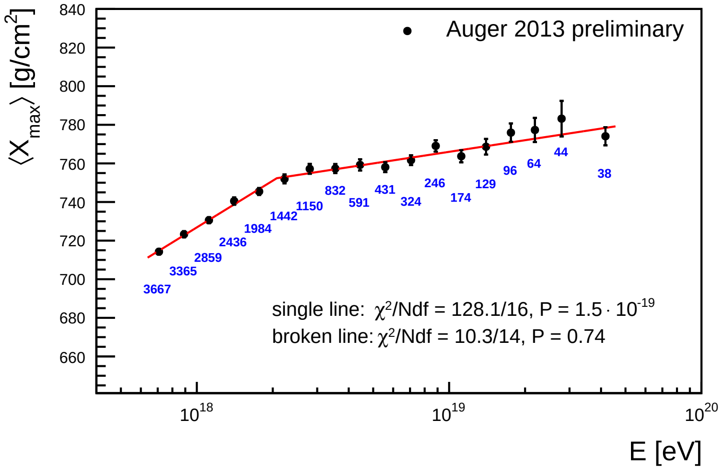




- $X_{\max}$ within the FD field of view
- fiducial volume cut to reject too distant showers
- cloud disturbance

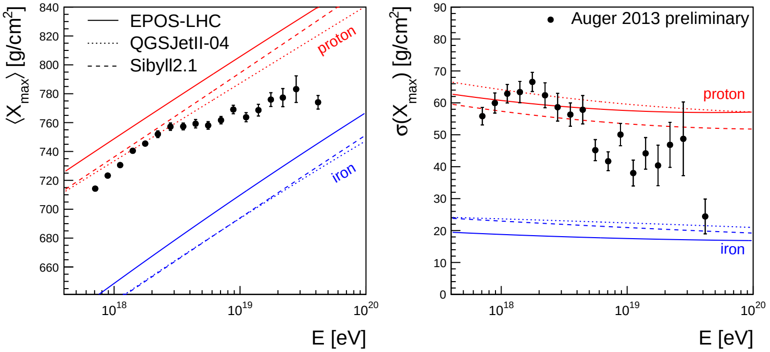
- Uncertainties for $< X_{\max} >$ due to reconstruction, event selection, atmospheric conditions are below 15 g/cm^2

Measurement of $< X_{\max} >$



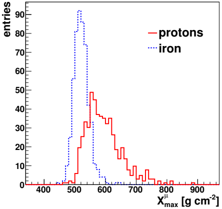
- $< X_{\max} >= \alpha(lnE- < lnA >) + \beta$
- $D_{10} = \frac{d< X_{\max} >}{dlnE} \approx \alpha(1 - \frac{d< lnA >}{dlnE})$

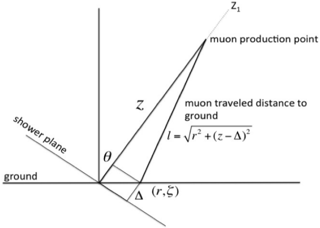
Measurement of $< X_{\max} >$ and $\sigma(X_{\max})$

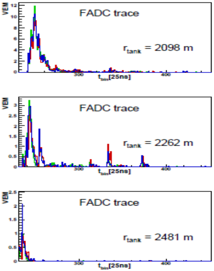


- The mass interpretation depends on the hadronic model
- Versions of EPOS and QGSJETTII tuned with LHC data

Muon Production Depth (MPD)

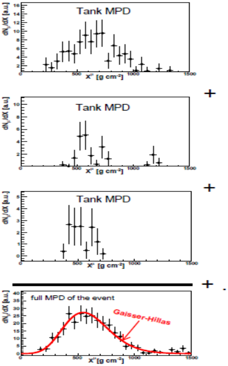






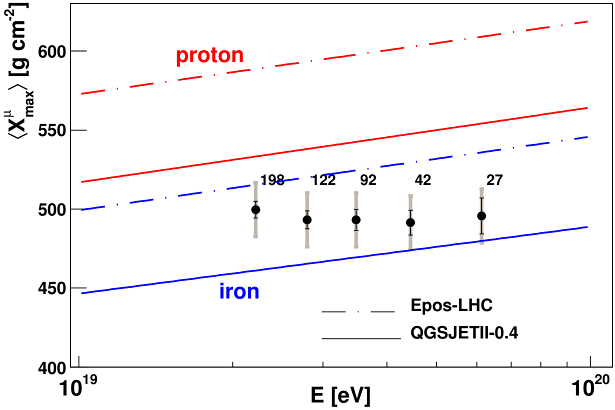
$$z = \frac{1}{2}\left(\frac{r^2}{ct} - ct\right) + \Delta$$

$$X^{\mu} = \int_z^{\infty} \rho(z')\, dz'$$



- Strategy of the analysis: reconstruct MPD(θ, r) from FADC traces
  - Inclined events to avoid the EM contamination.
  - Fixed zenith angle [55^o, 65^o] to avoid θ dependence.
  - SD detectors far from the core r $>$ 1700 m for reduced δX^{μ}

MPD Results



- The models do not reproduce equally all the shower parameters.
- The consistency with other independent mass estimators (X_{max}) will serve to constrain and improve hadronic models.

Neutron search

- Neutrons produce air showers that are indistinguishable from those produced by protons.
- Neutrons are electrically neutral. They can point back to the source.
- Neutrons are produced in pion-producing interactions, also producing gamma-rays.
- Event clustering would be indicative of a neutron cosmic ray flux.
- Even though neutrons are unstable outside the nuclei, at $E > 1$ EeV they still can reach us from Galactic sources, ie, ≈ 9.2 (En/EeV) kpc.
- A search over selected candidate source was performed (HESS, gamma ray and radio pulsars, microquasar, x-ray binaries...).
- No significantly small P-value was found for any of the classes of potential Galactic sources considered.
- Null results were also derived for the Galactic Plane and the Galactic Center.

These targeted searches significantly constrain models in which the observed EeV protons are produced by candidate sources in the Galaxy.

Conclusions

- Photon and Neutrino limits
  - Constrains on astrophysical source models
  - GZK region within reach in the next few years

- Nuclear mass
  - Measurements show a trend towards predictions of heavier primaries
  - Different measured parameters to constrain and improve hadronic models