Mass composition of Ultra High Energy Cosmic Rays at the Pierre Auger Observatory

Hernan Wahlberg for the Pierre Auger Collaboration

Universidad Nacional de La Plata

July 21-27 2011

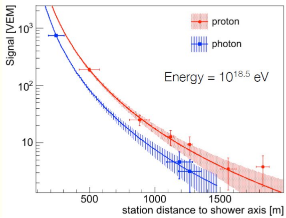
PIERRE AUGER OBSERVATORY

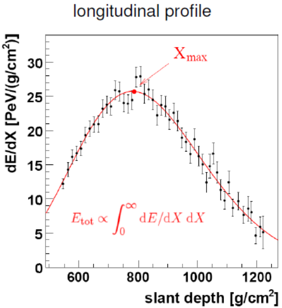
Europhysics Conference on High-Energy Physics

Grenoble - France

Outline

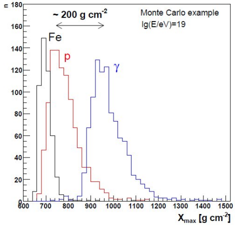
Photon identification



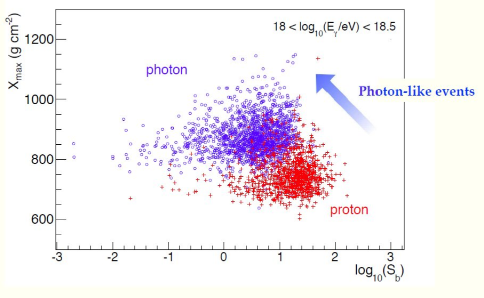


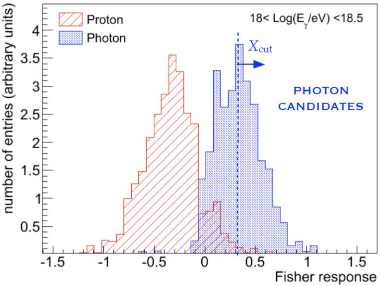
- SD:
  - Smaller signals
  - Fewer trigger stations
  - Sharper lateral distribution
- $$S_b = \sum_i S_i \left(\frac{R_i}{R_{ref}} \right)^b$$

- FD: Deeper X_{max}



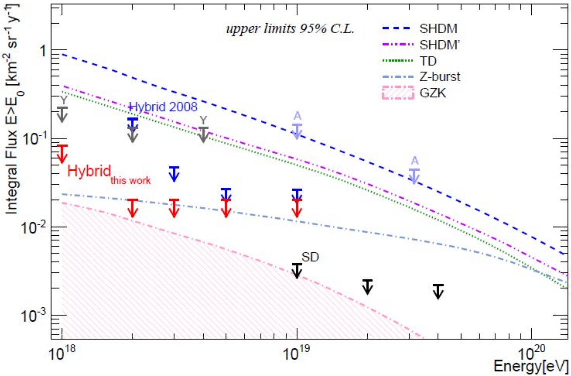
Photon selection





- Fisher Analysis
  - $F = a1.var1 + a2.var2$
- Photon efficiency 50$\%$
- Proton contamination $<$ 1 $\%$

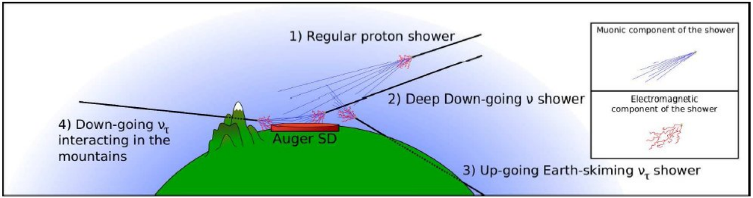
Photon limits



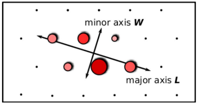
- No candidates over the expected background
- Top Down models disfavored
- GZK region within reach in the next few years using the hybrid data (in the EeV range) and the larger event statistics of SD (at the highest energies)

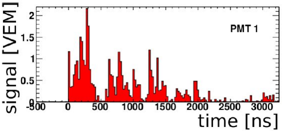
Neutrino identification

- The discrimination power is enhanced when looking at inclined showers
- Neutrinos identified as inclined young (deep) shower



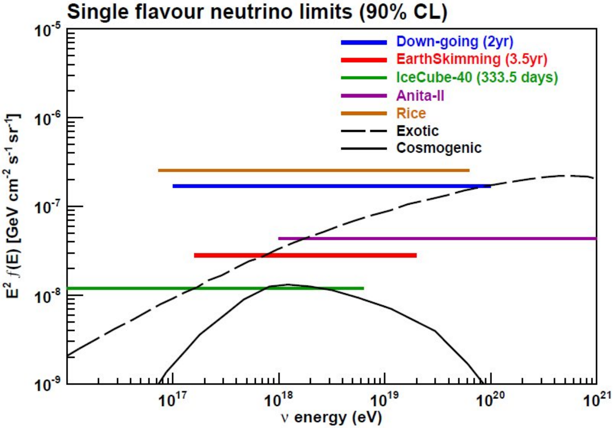
- Elongated footprint
- $\Theta > 75^o$
- Deep showers induce signals extended in time





Neutrino limits

- No candidates found
- Competitive limit to UHE neutrino flux
- Good sensitivity in the GZK expected region



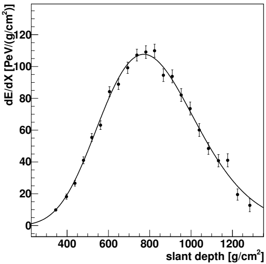
Nuclear mass

Information on the shower development can be extracted using both the Surface Detector(SD) and the Fluorescence Detector(FD) of the Pierre Auger Observatory

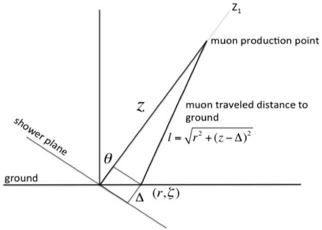
- From the Fluorescence Detector:
  - X_{max}
  - RMS(X_{max})
- From the Surface Detector:
  - Azimuthal asymmetry of signal risetime: Θ_{max}
    - The time structure of the signals recorded by the SD contains information on the shower development
  - Depth profile of muon production: X^{μ}_{max}
    - The depth along the shower axis where the number of produced muons reaches a maximum

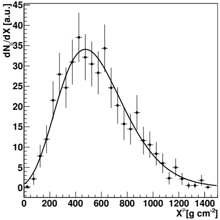
Longitudinal development

- X_{max}
  - Hybrid events (FD + 1SD station) have been used
  - Fluorescence and Cherenkov light signals: longitudinal profile of the energy deposit



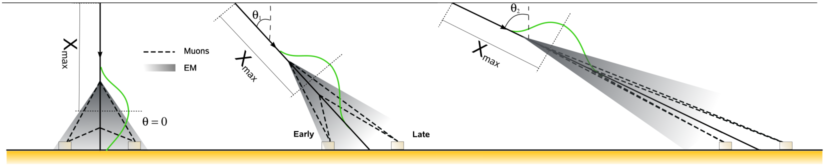
- Muon production distance (base on FADC traces of SD stations)
  - $55^o < \theta < 65^o$; r $>$ 1800 m ; E $>$ 20 EeV

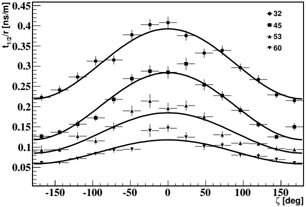




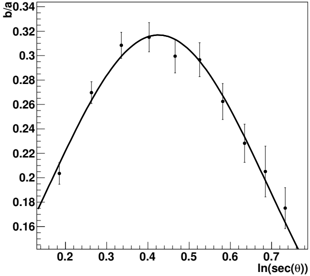
Signal asymmetry

- The azimuthal asymmetry of signal risetime depends on shower development



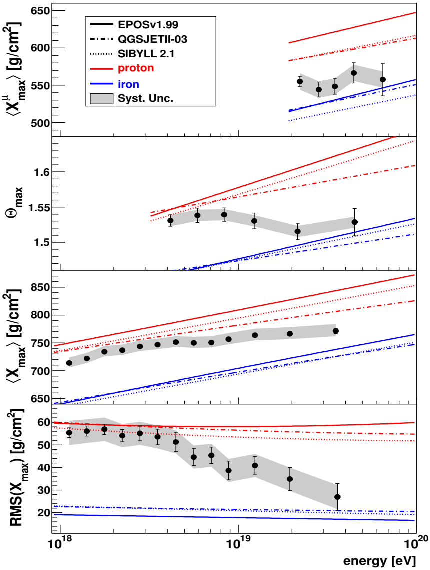


- $< t_{1/2}/r >= a + bcos(\zeta)$
- Statistical method to determine the evolution of the early-late asymmetry (b/a) with zenith angle
- Θ_{max} : $sec(\theta)$ for which b/a is maximum. Different for different primaries



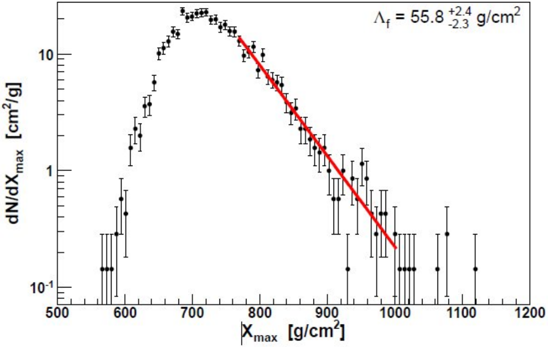
Nuclear mass results

- SD reach higher energies
- Compatible results of different observables with different systematics
- Assuming that the hadron interaction models are correct, the comparison of the data and simulation leads to the conclusion that the mean mass rises as the energy increases



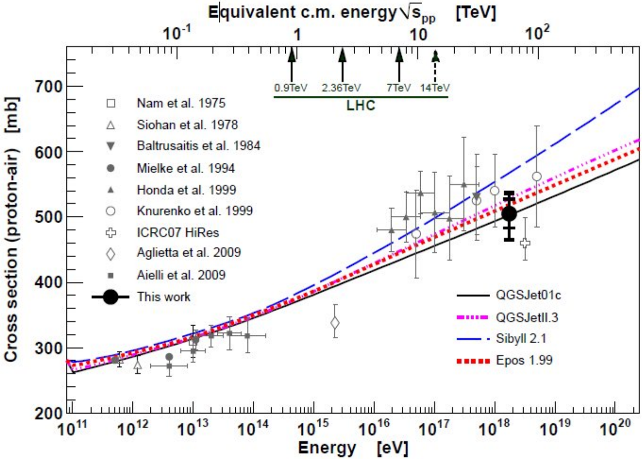
Cross Section observable

- X_{max} tail distribution
- $\Lambda_f = K_p.\lambda_{p-air}$



- Data selection
  - $10^{18} - 10^{18.5} eV$
  - Select the 20$\%$ most penetrating events

Cross Section determination



- Helium bias potentially most dangerous
- Total systematics on same level as statistical resolution

Conclusions

- Photon and Neutrino limits
  - Top-down models disfavored
  - GZK region within reach in the next few years using hybrid data (in the EeV range) and the larger event statistics of SD (at the highest energies)

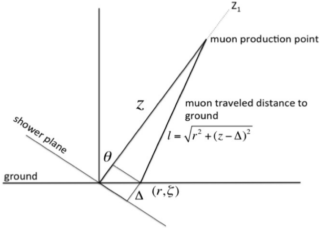
- Nuclear mass
  - All three measurements show a trend towards the prediction of heavier primaries
  - Provide tighter constrains for models and allow reducing systematics uncertainties on mass composition and cross section measurements

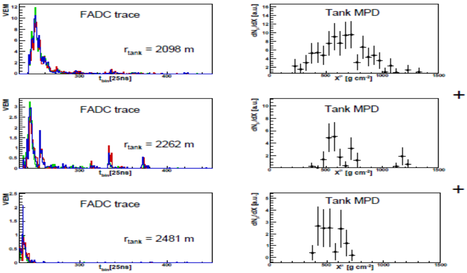
- Proton-Air Cross Section
  - Result favors a moderately slow rise of the cross section towards higher energies
  - First analysis at the LHC also indicate slightly smaller p-p cross-section than expected within many models

Backup Slides

Muon Production Depth (MPD)

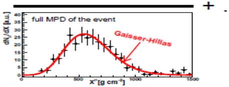
- Determine MPD distribution using FADC traces of SD stations
- Showers at 60^o and stations far from the core to minimize uncertainties (em contamination and resolution)

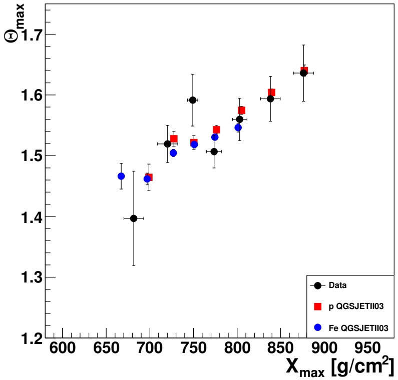




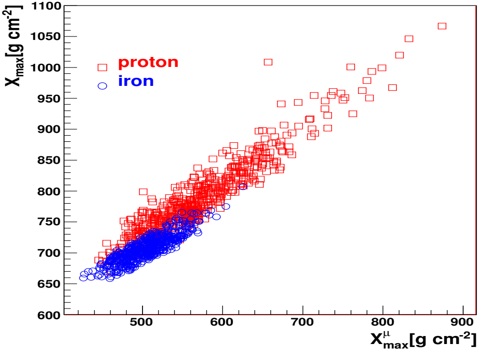
$$z = \frac{1}{2}\left(\frac{r^2}{ct} - ct\right) + \Delta$$

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





Θ_{max}
1.7
1.6
1.5
1.4
1.3
1.2
600
650
700
750
800
850
900
950
X_{max} [g/cm^2]
Data
p QGSJETII03
Fe QGSJETII03



X_{max}[g cm^{-2}]
1100
1050
1000
950
900
850
800
750
700
650
600
proton
iron
500
600
700
800
900
X^{μ}_{max}[g cm^{-2}]

Neutrinos

	Earth-skimming	Down-going
Inclined Showers	N° of Stations ≥ 3 $L/W > 5$ $0.29\,\frac{\mathrm{m}}{\mathrm{ns}} < V < 0.31\,\frac{\mathrm{m}}{\mathrm{ns}}$ RMS(V)$< 0.08\,\frac{\mathrm{m}}{\mathrm{ns}}$ -	N° of Stations ≥ 4 $L/W > 3$ $V < 0.313\,\frac{\mathrm{m}}{\mathrm{ns}}$ $\frac{\mathrm{RMS}(V)}{V} < 0.08$ $\theta_{rec} > 75°$
Young Showers	ToT fraction>0.6	Fisher discriminator based on AoP

$$\mathcal{E}^{\mathrm{DG}}(E_\nu) = \frac{2\pi}{m} \sum_i \left[\sigma^i(E_\nu) \int dt\, d\theta\, dD\, dS \right.$$
$$\left. \sin\theta\, \cos\theta\, \varepsilon^i(\vec{r}, \theta, D, E_\nu, t) \right]$$

$$f(E_\nu) = k \cdot E_\nu^{-2}$$