Measurements of the muon shower content at the Pierre Auger Observatory

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Methods to measure muon shower content

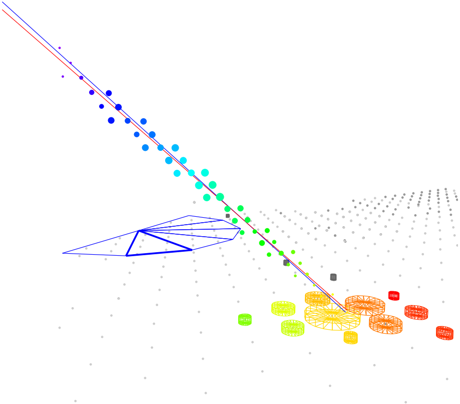
Measured shower characteristics

fluorescence detector

- longitudinal profile

surface array of water Cherenkov detectors

- lateral profile
- temporal profile sampled at 40 MHz



Direct methods

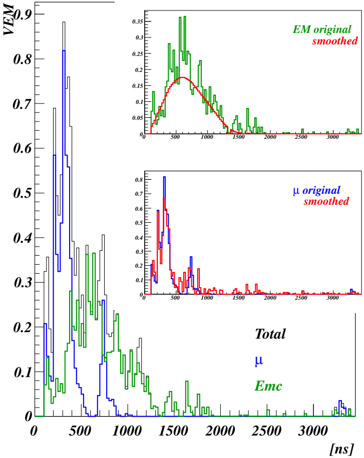
- using FADC traces in surface detectors
- horizontal showers

Indirect methods

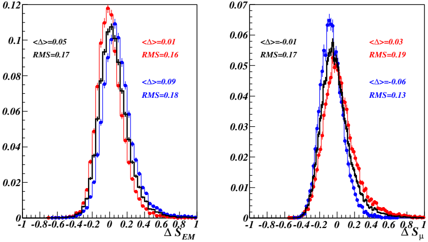
- shower universality
- fitting of individual hybrid events

Smoothing method

- the smoothing filter is applied to FADC traces to estimate EM signal in each station
- the convolute range is optimized to account for the functional dependence of the average muon pulse width on θ

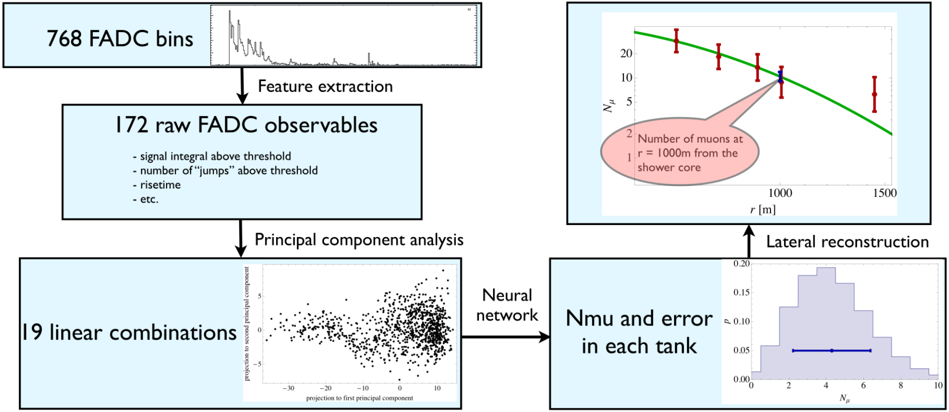


$$S_{\mathrm{tot}} = \underset{\text{smoothing}\nearrow}{\underline{S_{\mathrm{em}}}} + \underset{\nwarrow\text{by difference}}{\underline{S_\mu + S_\mu^{\mathrm{em}} + S_{\mathrm{hadr}}}}$$



- the estimates of S_μ and S_{em} are unbiased;
- background of high-energy γ's $< 10\%$;
- no dependence on hadronic models.

Multivariate muon counter



768 FADC bins

Feature extraction

172 raw FADC observables

- signal integral above threshold
- number of "jumps" above threshold
- risetime
- etc.

Principal component analysis

19 linear combinations

Neural network

Nmu and error in each tank

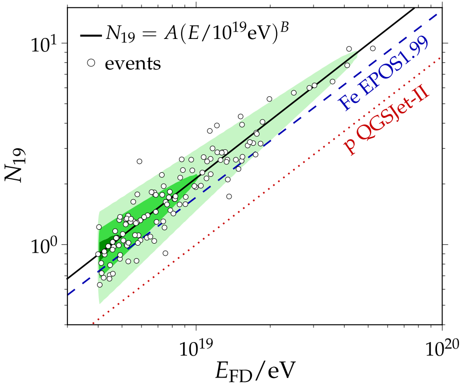
Lateral reconstruction

Number of muons at r = 1000m from the shower core

Inclined showers

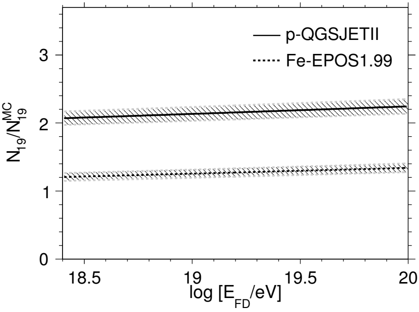
- showers size N_{19} is proportional to muon number;
- calibration of N_{19} with E_{FD} allows to estimate the muon deficit in simulations

$$\frac{N_\mu^{\text{data}}}{N_\mu^{\text{MC}}} = \frac{N_{19}^{\text{data}}}{N_{19}^{\text{MC}}} = \frac{A(E_{\text{FD}}/10\ \text{EeV})^B}{A_{\text{MC}}(E_{\text{FD}}/10\ \text{EeV})^{B_{\text{MC}}}}$$



$$N_\mu^{\text{rel}} = 2.13 \pm 0.04(\text{stat}) \pm 0.11(\text{sys})$$

with respect to p QGSJET II at 10 EeV

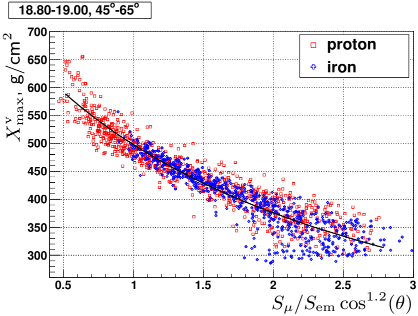


$S_\mu/S_{\rm em}$ shower universality

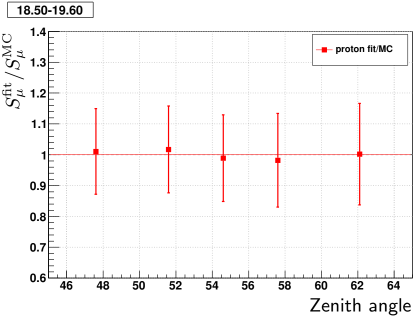
dependence of $S_\mu/S_{\rm em}$ on vertical depth of shower maximum $X^{\rm v}_{\rm max}$ is almost the same for all primary nuclei and energies

$$S_\mu^{\rm fit} = S_{\rm tot}/\left[1+\cos^\alpha(\theta)/\left((X^{\rm v}_{\rm max}/A)^{1/b}-a\right)\right]$$

universality for QGSJET II



S_μ estimate is unbiased, RMS 15%

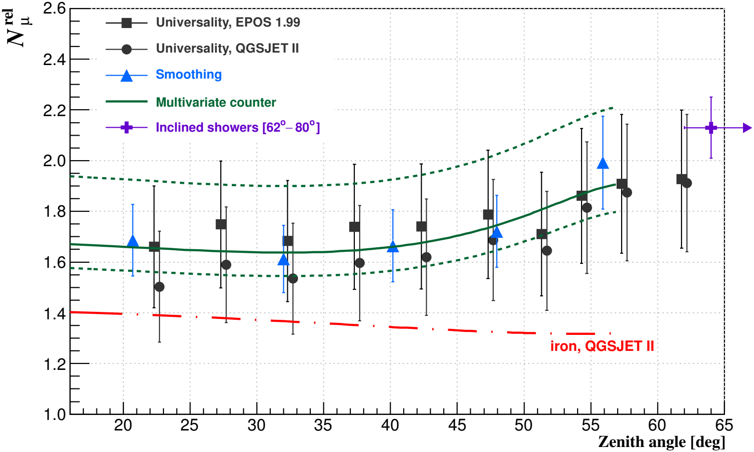


different $(A,\, a,\, b)$ for QGSJET II and EPOS 1.99 → model-dependent S_μ estimates in data

Application to data

data from 1 January 2004 till 30 September 2010

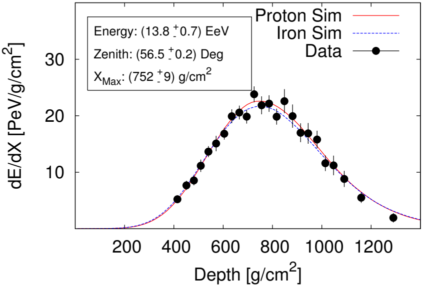
N_μ^{rel} — number of muons with respect to QGSJET II protons at 10 EeV

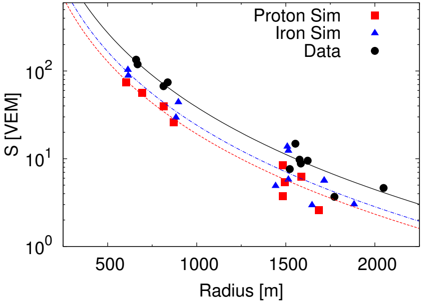


Fitting of hybrid events with QGSJET II

nominal FD energy, original QGSJET II signal

the same E, θ and longitudinal profile $\Longrightarrow$ the total signal is low





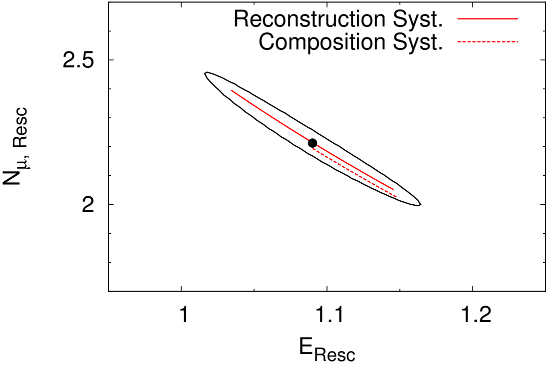
Rescaling of simulated signals

The rescaled signal in simulations

$$S_{\text{fit}} = N_{\mu,\,\text{resc}} E_{\text{resc}}^{\alpha} S_{\mu,\,\text{sim}} + E_{\text{resc}} S_{\text{em},\,\text{sim}}$$

- $N_{\mu,\,\text{resc}}$ increases the signal from hadronically produced muons
- E_{resc} increases the total ground signal

$$E_{\text{resc}} = 1.09 \pm 0.08^{+0.08}_{-0.06}\ ;\ N_{\mu,\,\text{resc}} = 2.21 \pm 0.23^{+0.18}_{-0.23}$$



Summary

Results on muon measurements

- smoothing method, multivariate counting and shower universality:
  $N_\mu^{\mathrm{rel}} \approx 1.6 - 1.7$ for $\theta < 45^\circ$
  $N_\mu^{\mathrm{rel}} \approx 1.9 - 2.0$ for $\theta > 55^\circ$
- inclined showers:
  $N_\mu^{\mathrm{rel}} = 2.13 \pm 0.04(\mathrm{stat}) \pm 0.11(\mathrm{sys})$

Fitting of hybrid events

not comparable directly with other methods

$E_{\mathrm{resc}} = 1.09 \pm 0.08^{+0.08}_{-0.06}\ ; N_{\mu,\,\mathrm{resc}} = 2.21 \pm 0.23^{+0.18}_{-0.23}$

- increases signal only from hadronically produced muons
- uses energy, longitudinal and lateral distributions of QGSJET II
- rescales signals by constant factor independently on the zenith angle

Discussion

Deficit of muons in simulations

- energy assignment uncertainty $\approx 22\%$;
- shortcomings in interaction models;
- mass composition.

Zenith angle dependence of N_{μ}^{rel}

- different attenuation of heavier primaries if they present in data;
- harder muon spectra in data.