Arrival time distribution of muons from extensive air showers

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Introduction

Upgraded detectors of the Pierre Auger Observatory

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Muonic signal

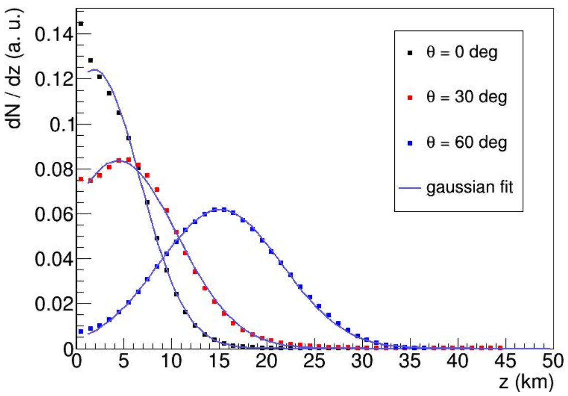
We studied:

- Muon production distribution in extensive air showers.
- Muon arrival time distribution at the observation level,
- Relation between arrival time and production profile in the atmosphere.

Using

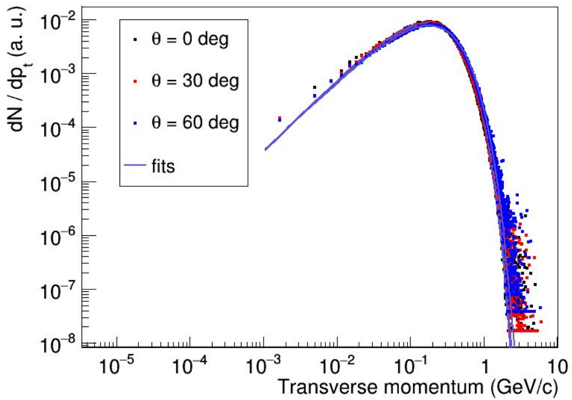
- CORSIKA simulation of showers initiated by proton, silicon and iron nuclei with energy of 10 EeV and zenith angles of 0, 30 and 60 degrees.

Muon production distributions



Distribution of production distance

- Defined along the z-axis.
- Distribution maximum increases for larger zenith angles.
- Fit to Gaussian function.

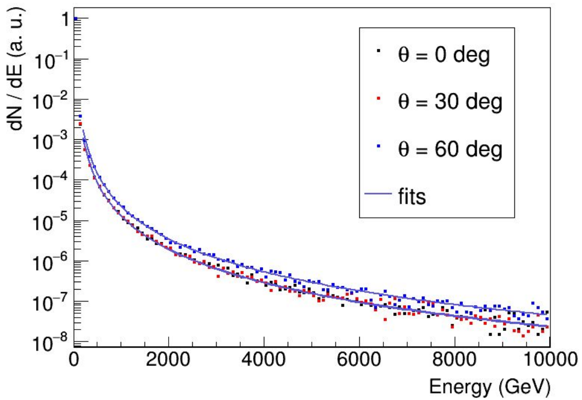


Distribution of transverse momentum

- Defined perpendicular to the z-axis.
- Fit with function:

$$f_p(p_t) = A p_t^{\lambda} \exp(-p_t/Q) \ .$$

- Found $\lambda = 1.317 \pm 0.012$,
  $Q = 129.58 \pm 0.73 \, \mathrm{MeV/c}$.



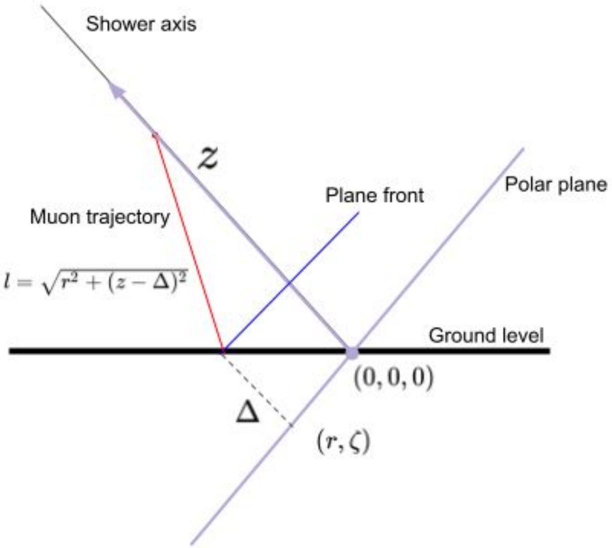
Distribution of production energy

- Weak dependence with zenith angle.
- Fit to a power law:

$$f_E(E) = B E^{-\gamma}$$

- Found $\gamma = 2.727 \pm 0.002$.

Muon arrival delay at the observation level



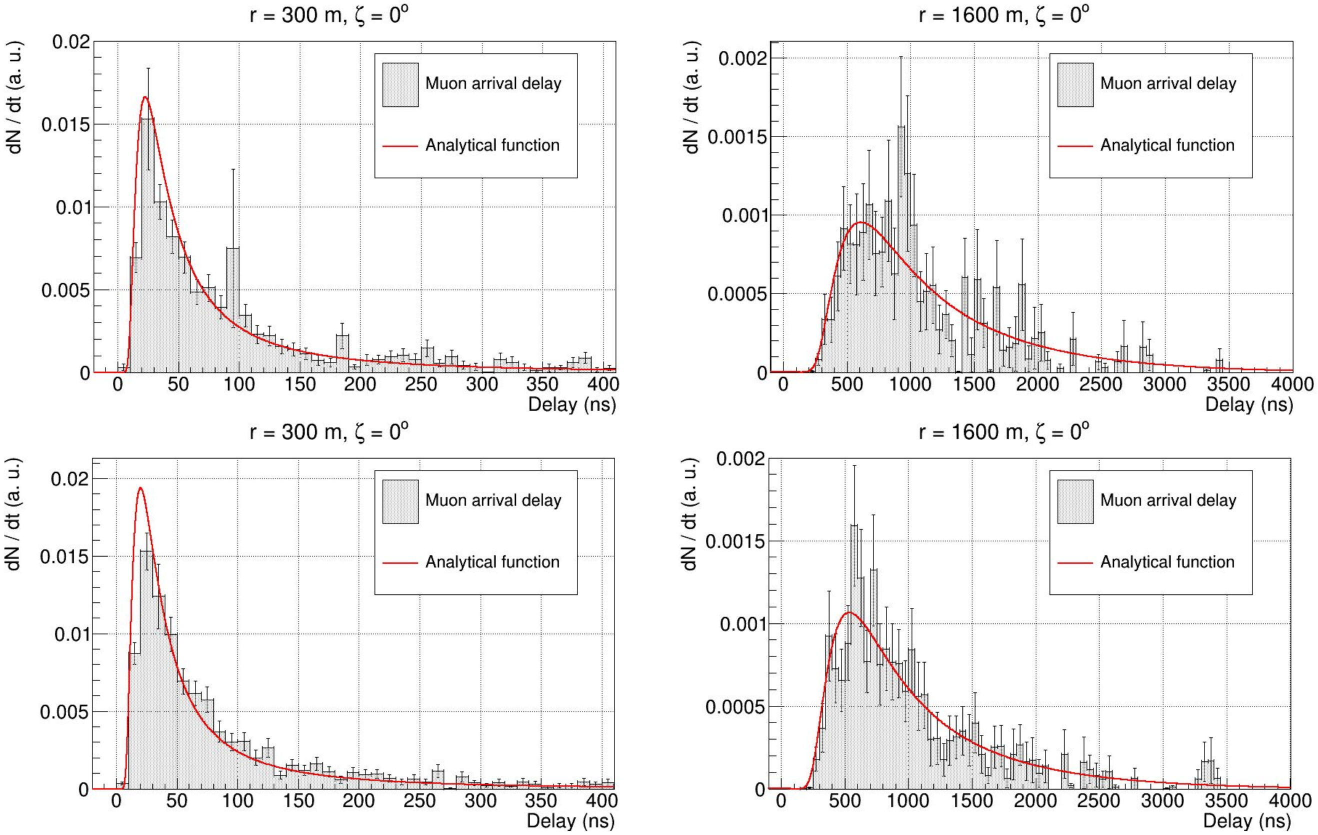
Muon delay at observation level is defined with respect to a plane front travelling at the speed of light.

Type of delay	*Description*	*Distribution*
Geometrical delay	Path difference between muon trajectory and plane front propagation.	$g(t_g) = \frac{dN}{dt_g} \equiv -\frac{1}{N_r}\frac{d^2N}{dt_g dr} = -\frac{dN}{dz}\frac{dz}{dt_g}\frac{1}{N_r}\int \frac{d^2N}{dEdr}[z]dE$
Kinematic delay	Muon delay compared to a particle travelling at the speed of light.	$\epsilon(t_\epsilon) = \frac{dN}{dt_\epsilon} \equiv -\frac{1}{N_r}\frac{d^2N}{dt_\epsilon dr} = -\frac{1}{N_r}\frac{d^2N}{dEdr}\frac{dE}{dt_\epsilon}$
Total delay	Convolution of geometrical and kinematic distributions.	$\frac{dN}{dt} = g(t) \otimes \epsilon(t)$

Muon delay distribution at the observation level

Proton

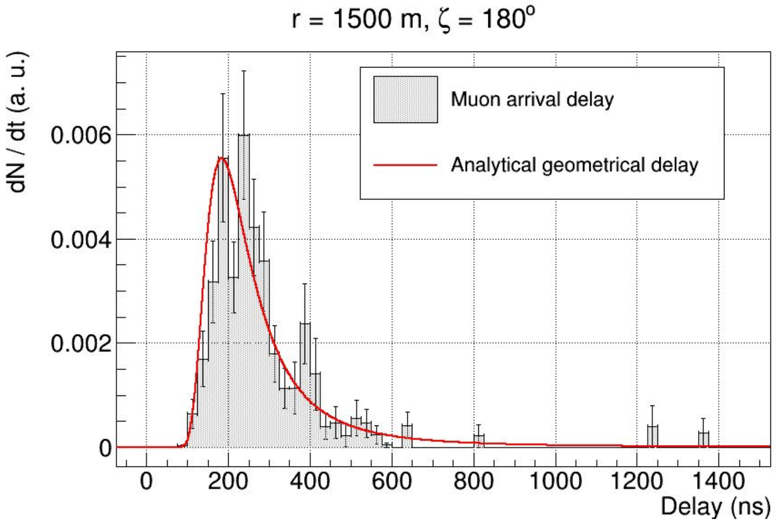
Iron

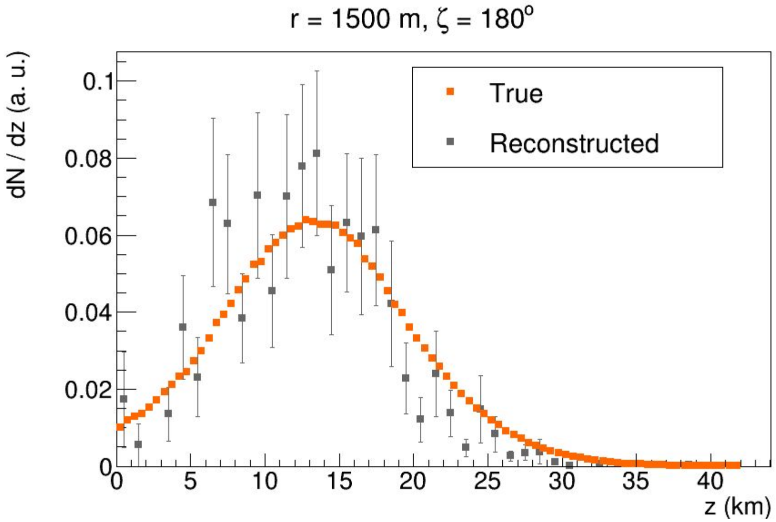


Primaries with energy of 10 EeV and zenith angle of 30 degrees.

Reconstruction of muonic profile in the atmosphere

Proton, 10 EeV, 60 degrees.





For distances from the shower core larger than 1000 m, the geometrical delay can be used to describe the muon arrival time distribution.

Using a relation between the geometrical delay and the muon production distance the muonic profile in the atmosphere was reconstructed.

Summary and outlook

- We used simulations of extensive air showers to study the muon production distributions of distance, transverse momentum and energy.
- The distributions of muon arrival delay at the observation level was compared with an analytical description and agreement was found.
- The muonic production profile in the atmosphere was reconstructed using a relation between the geometrical delay and production distance distribution.
- A method can be developed to use the muonic signals from the upgraded detectors of the Pierre Auger Observatory to reconstruct muonic profiles and obtain observables that relate to the composition of the primary cosmic rays.

Acknowledgements

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