Arrival time distribution of muons from extensive air showers

Allan Machado Payeras and Anderson Campos Fauth
University of Campinas, Brazil

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1. Abstract

Since the upgraded surface detectors of the Pierre Auger Observatory will provide information about the signals due to muons from extensive air showers, we studied their production distributions as well as their arrival time at the observation level. Agreement with analytical descriptions was found. We also investigated a relation between the muon arrival time and their production profile which is relevant for composition studies.

2. Introduction

- Simulation of extensive air showers produced with the CORSIKA software.
- Cylindrical coordinate system for shower description.
- Muon arrival delay at ground level defined with respect to a plane front moving at the speed of light along the z-axis.

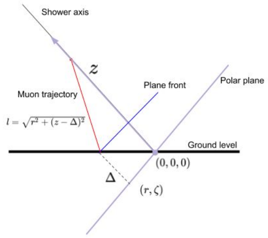

Figure 1: Cylindrical coordinate system used for the analyses.

3. Muon production distributions

Distribution of muon production distance

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

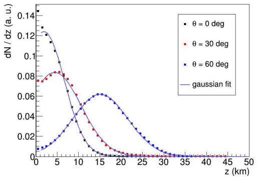

Figure 2: Normalised distribution of muon production distance. Protons of 10 EeV.

Distribution of muon transverse momentum

- Defined perpendicular to the z-axis at muon production time.
- Fit with function:

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

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

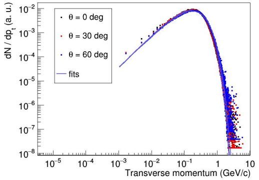

Figure 3: Normalised distribution of muon transverse momentum. Protons of 10 EeV.

Distribution of muon production energy

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

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

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

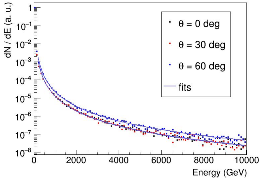

Figure 4: Normalised distribution of muon production energy. Iron nuclei of 10 EeV.

4. Arrival time and profile reconstruction

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.	$\frac{dN}{dt} = g(t) \otimes \epsilon(t)$

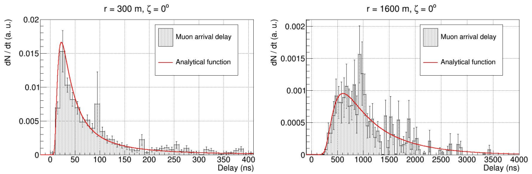

Figure 5: Normalised distribution of muon arrival time from CORSIKA simulation. Red line shows analytical function obtained from convolution of geometrical and kinematic distributions. Shower initiated by proton of 10 EeV and zenith angle of 30 degrees.

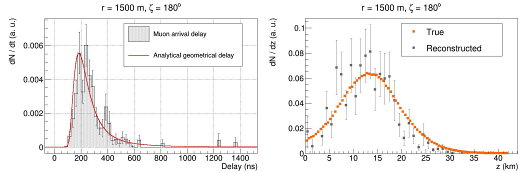

Figure 6: *Left:* muon arrival distribution and analytical description using only geometrical delay. *Right:* reconstruction of muon production profile using geometrical delay description and comparison to true distribution. Proton of 10 EeV and zenith angle of 60 degrees.

5.Summary

- Using CORSIKA simulations of extensive air showers the muon distributions of production distance, transverse momentum and energy were fitted to functions and the corresponding parameters were obtained.
- The distributions of muon arrival delay, obtained from the simulations for different distances to the shower core, are consistent with the analytical description in terms of the geometrical and kinematic delays.
- For distances r > 1000 m from the shower core, the approximation of the muon distribution of arrival time with the geometrical delay was used to reconstruct consistently their production profile.

6.Acknowledgments

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7. References

[1]. A. Aab et al., *Nucl. Instrum. Methods Phys. Res.*, Sect A **798** (2015) 172.
[2]. A. Aab et al., *arXiv:1604.03637* (2016).
[3]. D. Heck et al., Forschungszentrum Karlsruhe, fzka-6019 ed., 1998.
[4]. L. Cazón et al., *Astropart. Phys.* **21** (2004) 71.
[5]. L. Cazón et al., *Astropart. Phys.* **36** (2012) 211.