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MONTE-CARLO SIMULATION OF MUON DIRECTION FOR PARTICLE ASTRONOMY APPLICATIONS

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Abstract. We report on the Monte-Carlo simulation results in order to see the difference between the cosmic ray primary particle's angle of incidence and the muon's azimuth. The simulations have been performed using the CORSIKA code applied for different primary particle energies and incident angles. The CORSIKA code is a versatile program for particular simulation of cosmic ray extensive air showers induced by high energetic primary cosmic rays. The observed difference between the primary particle's incident angle and the muon azimuth is smaller with the increase of the muon's energy. The difference decreases from several degrees up to less than 0.1 degrees for muon's energies greater than 150 GeV. Based on the results we had started some simultaneous measurements of the underground muon flux correlated with observation of the sky by using an optical telescope. The measurements of the muon flux are currently in progress using the directional detector (Si-RO) located in the underground laboratory of IFIN-HH from Slanic Prahova.

Key words: cosmic rays, Monte-Carlo simulation, particle astronomy, muon.

1. INTRODUCTION

Cosmic rays are energetic, subatomic particles that arrive from outside the Earth's atmosphere. Cosmic rays arrive with a variety of energies, the lowest energy cosmic rays are produced by ordinary stars like the Sun. Scientists suspect other sources large structures such as active galactic nuclei or colliding galaxies might be candidate objects which produce or accelerate these cosmic rays. The source for these very energetic particles, however, is still unknown. The energy spectrum covers more than 21 orders of magnitude. The measurements of the spectrum of the primary cosmic rays could be performed by direct measurements for energy $< 10^{14}$ eV. For higher energy, where the flux could be lower than 1 particle/km^2 · century, the spectrum could be measured only by indirect experiments that cover large areas at the surface of the Earth (KASCADE Grande [1], AGASA [2], AUGER [3], etc).

One of the newest component of cosmic ray physics is the particle astronomy. The methods are based both on primary cosmic ray measurements – proton or gamma astronomy and on secondary cosmic ray measurements – muon astronomy. For primary particle astronomy, some new results have been recently reported by Pierre Auger Observatory [4]. For muon astronomy, data regarding the Moon or the Sun's shadows have been presented by underground laboratory of Soudan [5].

2. MONTE-CARLO SIMULATIONS

CORSIKA (COsmic Ray SImulations for KAscade) [6] is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries. CORSIKA may be used up to and beyond the highest energies of 100 EeV. The most actual version is CORSIKA 7.5000 (February 26, 2016).

The simulations have been performed using different primary particle of different energies and incident angles. Taking in to account the conditions from the underground laboratory of IFIN-HH from Slanic Prahova Romania [7, 8], different energy cuts have been applied in order to estimate the azimuth angle's variation of the mouns compared with the primary particle ones.

Figures 1 and 2 present the difference between the primary particle's azimuth and the muon's incident angle for different energy cuts (left) and for all muons (right). Figure 3 shows similar data as one from Figs. 1, 2, but for a realistic distribution of primary particle's direction and energy.

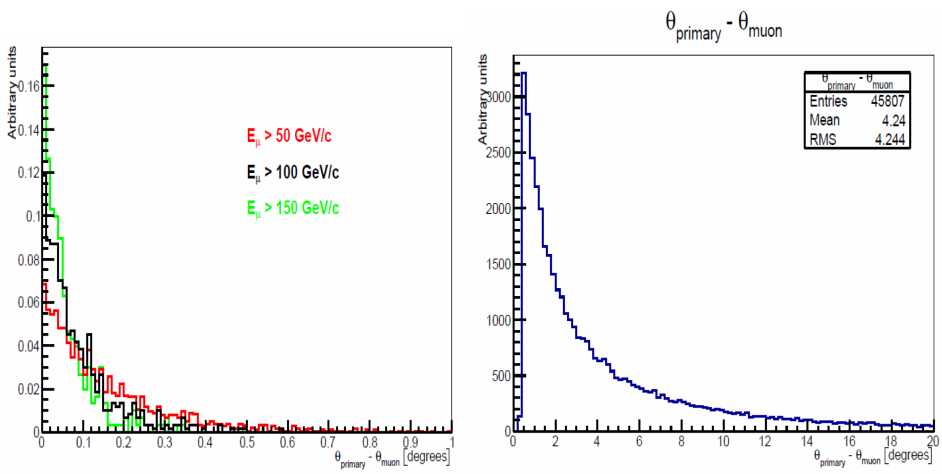

Fig. 1 – The difference between the primary cosmic ray's azimuth and the muon direction for $E_{primary} = 10^{16}$ eV, $\Theta_{primary} = 20°$, for 3 different energy cuts (left) and for all muons (right).

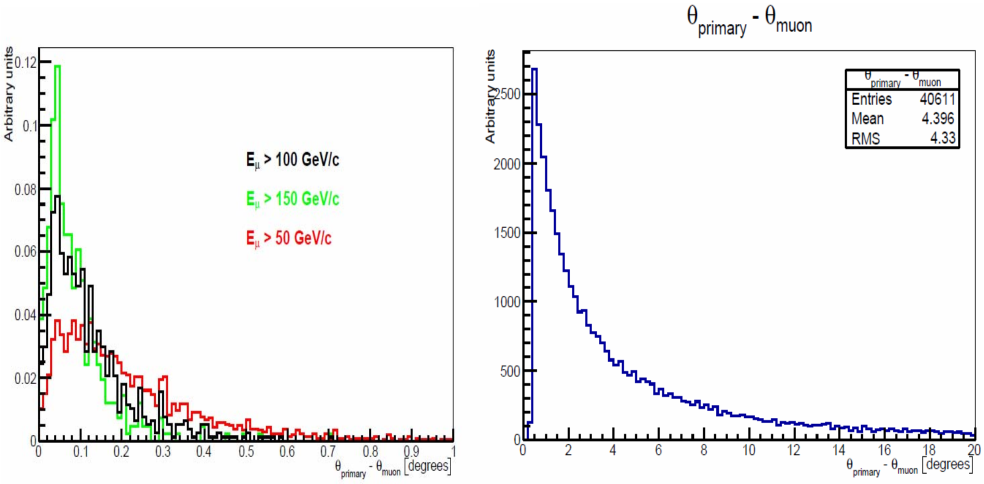

Fig. 2 – The difference between the primary cosmic ray's azimuth and the muon direction for $E_{\text{primary}} = 10^{16}$ eV, $\Theta_{\text{primary}} = 0°$, for 3 different energy cuts (left) and for all muons (right).

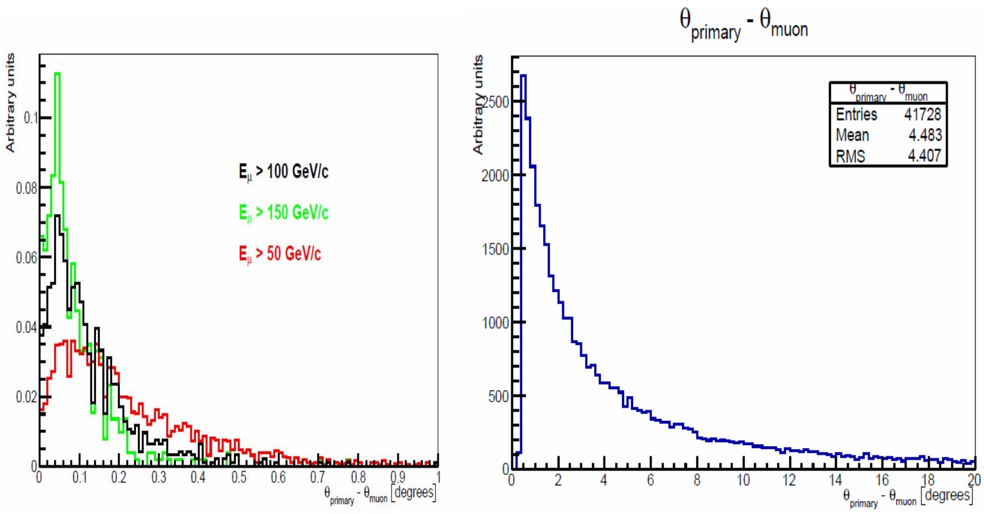

Fig. 3 – The difference between the primary cosmic ray's azimuth and the muon direction for $E_{\text{primary}} = 10^{14}$–$10^{17}$ eV, $\Theta_{\text{primary}} = 0°$–$45°$, for 3 different energy cuts (left) and for all muons (right).

Figure 4 presents a comparison between the muon and primary's incident angles difference for 3 energy cuts and for all muons on the same plot. For a better quality, the results have been normalized. The results of the simulations have been summarized in Table 1.

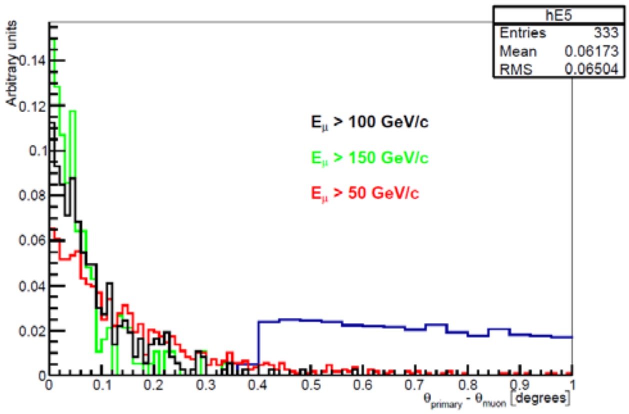

Fig. 4 – The difference between the primary cosmic ray's azimuth and the muon direction for 3 different energy cuts (green, black and red lines) compared with no energy cut (the blue line).

Table 1

The summarize of the simulation results

$E_{primary}$ [eV]	$\theta_{primary}$ [degrees]	$E_{\mu-cut}$ [GeV]	$\theta_{primary} - \theta_{\mu}$ [degrees]
10^{16}	20	No cut	4.24
		50	0.15
		100	0.08
		150	0.06
10^{16}	0	No cut	4.39
		50	0.23
		100	0.12
		150	0.09
10^{14}–10^{17}	0–45	No cut	4.48
		50	0.23
		100	0.12
		150	0.09

3. THE INFRASTRUCTURE

During the last decade IFIN-HH have developed a modern underground laboratory in Unirea salt mine from Slanic Prahova, Romania [7]. The laboratory is presently used for low background gamma spectrometry, radiation metrology, cosmic ray physics and nuclear astrophysics research.

One of the cosmic ray muon telescope located in the underground laboratory is the SiRO detector [9]. The detector is consisting of 6 active layers, each layer consisting of 24 scintillator plates read it out by optical fiber and Silicon-Photomultiplier (SiPM). The active layers are arranged in a way that permits a good quality in muon's angle reconstruction.

The Silicon-Photomultiplier (SiPM) [10] are semiconductors based photo-sensors that offer several advantages compared to other photo detection devices, like the classical photomultipliers. SiRO is designed for flux measurements and arrival direction similarity of cosmic muons.

Fig. 5 – The detector from the underground laboratory of IFIN-HH,
from Slanic Prahova salt mine [7].

Figures 5 shows an image of the detector. Figure 6 presents a valid muon event in underground as seen by the data acquisition program.

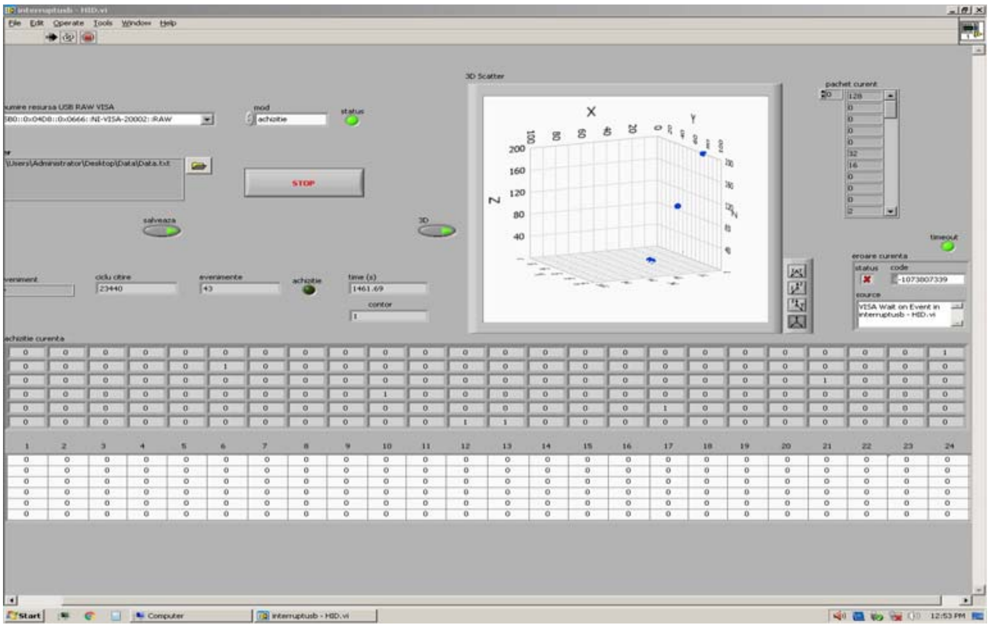

Fig. 6 – Display of a valid muon event in the underground detector.

In addition, the muon measurements will be performed in coincidence with optical observation of the sky based on the use of a modern telescope [11]. We propose to observe several points from the sky with interesting luminosity properties, like quasars or pulsars.

4. SUMMARY AND FUTURE PLANS

Since the origin of high energy cosmic rays is unknown, galactic or extra-galactic sources are presently, under investigation on different laboratories over the World. The identification of the primary particle's source is a very important information in order to find more data about the high energy interactions, history of the Universe, cosmology.

The high energetic muons can be used for the purposes of the present work by measurements of the muon flux in underground of the salt mine from Slanic Prahova, Romania. The simulation results show that the difference between the primary particle's direction and the muon's one is smaller with the increase of muon's energy. From the plots, one can observe that for a highest energy cut of the difference between the primary particle's incident angle and the muon ones is the smallest. We conclude that only the very energetic muons (E > 150 GeV) can be used for the identification of the primary particle's origin.

The measurements of the cosmic muon directional flux in Slanic Prahova has been started and the optical observation of the sky map will also be in operation from the second part of July 2017. We consider that preliminary results regarding the identification of possible high energy cosmic ray's sources (galactic or extra-galactic) can be available till the end of 2017.

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