# Optimizing the zenith angle dependence of cosmic ray muons from Charm particles in the knee region: simulation study

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**Abstract.** The muonic component of air showers is one of the most abundant component of charged particles arriving at the Earth's surface, and able to penetrate deeply underground, and is very sensitive to the primary mass and energy of the initial cosmic particle. Atmospheric muons are produced in the propagation of different components of extensive air showers. Therefore, variations in the muon ratio, defined as the number of positive over negative charged muons, must be well understood. In this paper, we study the variation of the muon charge ratio of cosmic muons at different zenith angles, and we study the contribution of charm particles in producing atmospheric muons using Monte Carlo showers initiated by two cosmic primaries, proton and iron, with four energies [10 PeV, 100 PeV, 1 EeV, 10 EeV], in the zenith range of [$0^\circ$ to $60^\circ$].

## 1. Introduction

High energy cosmic rays do not simply travel through the Earth's atmosphere. Instead, they interact with nuclei and create huge cascades of high energy secondary cosmic particles, called Extensive Air Showers (EAS) [1], whose main components are the electromagnetic, hadronic, muonic and neutrino components. Up to energies $4 \times 10^{15}$ eV (the knee [2]), cosmic radiations are assumed to originate inside our galaxy, and an extra-galactic origin is assumed at higher energies. By measuring the distribution of arrival directions of ultra-high energy cosmic rays, the Pierre Auger collaboration showed that particles with energies above $8 \times 10^{18}$ eV have an extra-galactic origin [3, 4]. However, cosmic ray sources and propagation processes are still under investigation. Therefore, accurate analyses of different components of the cosmic air shower can be very useful to understand the properties of these very energetic particles.

The energy spectrum of cosmic rays as measured by various experiments follows a smooth power law over many decades of energy ($dN/dE \sim E^{-\gamma}$, $\gamma$ is the spectral index), with two main features observed along the energy spectrum. A steepening in the energy spectrum is observed at about ($3 - 4 \times 10^6$ GeV), generally called the knee where the spectral index changes from about $\sim 2.7$ to about $\sim 3.0$. A flattening in the spectrum is also observed at about $\sim 10^{10}$ GeV, called the ankle with a change in the spectral index from $\sim 3$ to $\sim 2.6$. Cosmic rays with energies below the knee are thought to be originated in our galaxy. For energies beyond the ankle, cosmic rays are assumed to be from an extra-galactic origin. The energy region between the knee and the ankle is considered in theoretical models, such as the ankle model, the mixed composition

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model [5], and the dip model [6], to be a transition region from Galactic to extra-galactic origin of cosmic rays. Therefore, a solid understanding of these structures in the energy spectrum may provide valuable information to distinguish between cosmic ray sources.

Extensive air showers contain a small number of charm particles, however the effect of charm particles can be crucial in the development of extensive air showers. Above a certain energy $\approx 10^7$ GeV, charm particles carry a large portion of the energy of the primary cosmic ray, they will be able to reach large atmospheric depth and interact deep in the atmosphere. This can have a clear effect on the shape of the longitudinal profile of the energy deposited in the atmosphere, and in particular on the $X_{max}$. At lower energies, charm particles can decay very quickly, therefore, their contribution is considered to be very small and is generally neglected in extensive air shower measurements because of the leak of precise information about their properties. However, they have a longer lifetime for high energies, which leads to a decay length of several kilometers in the atmosphere. The purpose of this letter is to discuss the properties of muons from the charm particles component. The Monte Carlo simulation toolkit used to simulate cosmic particles will be first introduced, then the muon component properties will be discussed for the simulated cosmic ray primaries.

## 2. SIMULATION

We use the Monte Carlo air simulation software CORSIKA (Cosmic Ray Simulation for KASCADE) [7] for the simulation of cosmic air showers. CORSIKA allows us to choose between hadronic interaction models at low and high energies. Therefore, simulation of hadronic interactions processes at high energies ($> 80$ GeV) are produced using the hadronic interaction model SIBYLL2.3c [8]. In addition, FLUKA [9] is used to describe interactions of lower energies, and EGS4 [10] for the electromagnetic processes. We chose using CORSIKA because it allows to include or not charm and bottom particles in the first interactions of primary particle. Therefore, the simulation is repeated with and without charm particles. EAS initiated by proton and iron are considered as the two extreme cases for the primary mass assumption. We simulate 500 air showers for protons and irons with energy of [10 PeV, 100 PeV, 1 EeV, 10 EeV], incident with a zenith angle (0° - 60°) and over a 360° azimuth angle. The simulation is produced assuming the Central European Atmosphere for June 13, 1993. In order to study the zenith dependence, the simulation is divided in two zenith bands, vertical ($0° - 40°$) and inclined dataset ($40° - 60°$).

## 3. RESULTS AND DISCUSSION

The muon charge ratio is represented by the number of positive $N_{\mu^+}$ over negative $N_{\mu^-}$ charged atmospheric muons:

$$R_{\mu}^{atm} = \frac{N_{\mu^+}}{N_{\mu^-}} \tag{1}$$

The muon charge ratio is considered an important parameter to describe the muon component of air showers. Up to about 200 GeV/c of momentum, a constant muon charge ratio was obtained from measurements of various experiments, and then the ratio increases at higher momenta [11, 12]. Measurements of the charge ratio can provide relevant information for both cosmic ray properties and particle physics studies, help to better understand the hadronic interaction models, study the effect of the Earth's magnetic field on the primary and secondary component of cosmic rays, and provide a better prediction of the neutrino atmospheric flux. Therefore, it is important to study atmospheric muons from all component of extensive air showers, including charm particles.

Extensive air showers lose part of their energy in their propagation in the atmosphere because of their interaction with air molecules. In addition, the effect of the magnetic field of the Earth on the flux of cosmic rays causes an East-West asymmetry [13, 14, 15]. The azimuthal variation

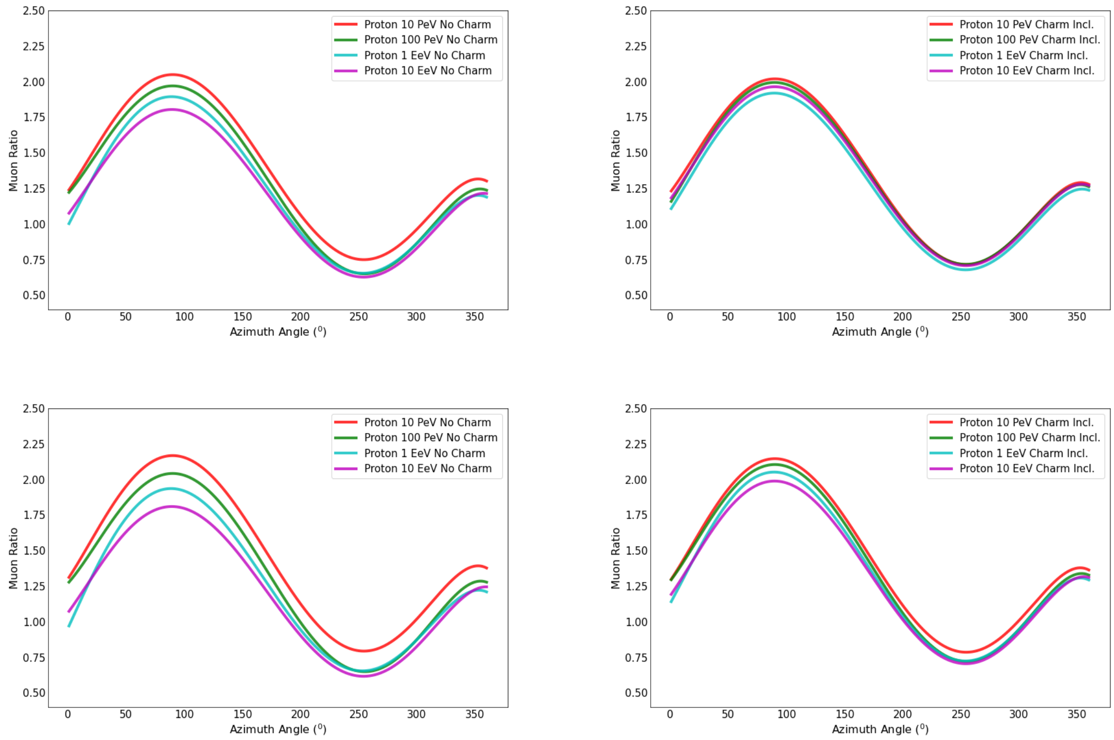


**Figure 1.** Muon charge ratio as a function of the azimuth distribution for vertical (top) and inclined (bottom) induced proton air showers, with charm particles included in the simulation (Right) and without (Left).

of the muon charge ratio in the four simulated energies, with and without muons from charm particles included in the simulation, is presented in Figure 1 and Figure 2 for vertical and inclined proton and iron primaries, respectively. In the absence of muons from charm particles, a more pronounced variation in the muon charge ratio, for different energies, is observed in induced proton showers than iron showers. This can be due to the larger number of muons produced from iron showers compared to the number of muons from proton showers. The amount of atmosphere that showers need to traverse is larger for inclined than vertical showers. Therefore, inclined showers are more attenuated in the atmosphere. Consequently, the variation in the muon ratio is larger for inclined showers for different energies.

Furthermore, the muon charge ratio is directly dependent on the energy and mass composition of the primary cosmic particle, used in the simulation. This is related to the different level of interaction in the atmosphere for different induced primary showers, and consequently leads to different stage of development at the surface. Figure 3 and Figure 4 show the muon charge ratio when in simulations muons from charm particles are included divided by the muon charge ratio without including muons from charm particles as a function of the distance to the shower axis. The radial dependence is shown for vertical (left) and inclined (right) proton 3 and iron 4 air showers, with and without charm particles. The variation in the muon charge ratio increases at large distances from the shower axis. In addition, a clear energy dependence is observed in the muon charge ratio for both proton and iron primaries.

Moreover, the variation of muon charge ratio and energy dependence are less pronounced when including muons from charm particles. The variation in the relative muon charge ratio

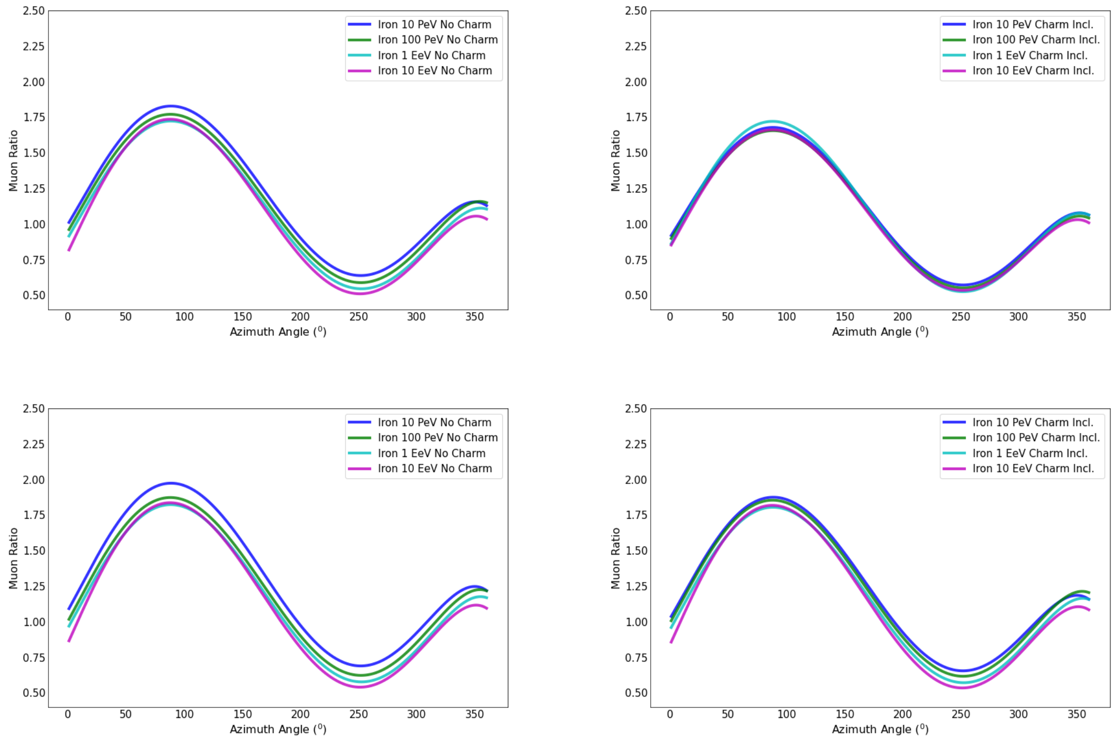


**Figure 2.** Muon charge ratio as a function of the azimuth distribution for vertical (top) and inclined (bottom) induced iron air showers, with charm particles included in the simulation (Right) and without (Left).

with and without charm muons showers shows a clear difference between vertical and inclined showers. Inclined showers has to travel for longer distances in the atmosphere, which makes their fluctuation larger than the case of vertical showers. In addition, this fluctuation in the relative muon charge ratio is smaller in the case of iron showers than proton showers. This could be due to the larger number of muons in iron showers that make it more probable to detect them at large distances from the shower axis.

## 4. Conclusions and Outlook

We have investigated the contribution of muons from charm particles in the muon charge ratio of cosmic air showers using Monte Carlo simulations for vertical and inclined proton and iron cosmic primaries with four fixed energies [10 PeV, 100 PeV, 1 EeV, and 10 EeV]. CORSIKA is used to simulate the propagation of extensive air showers in the atmosphere. SIBYLL2.3c is used to describe the hadronic interaction processes at high energies, FLUKA at low energies, and EGS4 to describe the electromagnetic processes. Inclined primaries showed a larger variation in the muon charge ratio than vertical primaries. In addition, this variation is smaller for iron primaries than proton primaries. A variation in the muon ratio is observed under the effect of the inclination of the air shower and the radial distance from the shower axis.

Besides giving insight into the effect of including muons from charm particles in the simulation, such analysis enables us to look at the variation of the muon charge ratio with the azimuthal distribution. In addition, simulating air showers produced by two primaries, proton and iron, is very important to discuss the variation in the muon charge ratio for different

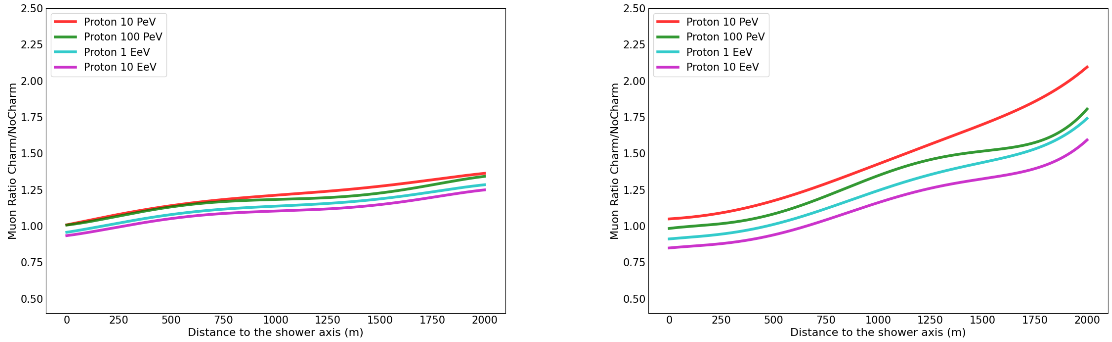


**Figure 3.** The ratio of muon charge ratio of vertical (left) and inclined (right) proton induced air showers as a function of the distance to the shower core, with and without muons from charm particles, and at four fixed energies [10 PeV, 100 PeV, 1 EeV, and 10 EeV].

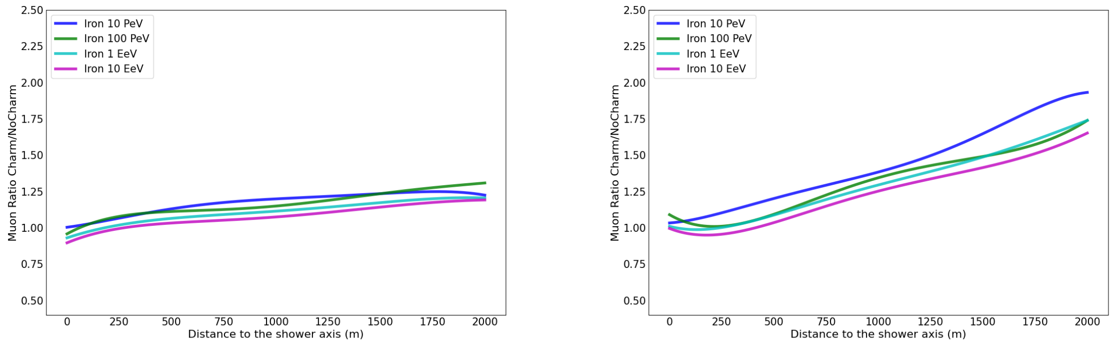


**Figure 4.** The ratio of muon charge ratio of vertical (left) and inclined (right) iron induced air showers as a function of the distance to the shower core, with and without muons from charm particles, and at four fixed energies [10 PeV, 100 PeV, 1 EeV, and 10 EeV].

masses. In future analyses, one can discuss the effect of including muons from charge particles on the transverse momentum distributions of different particles. It will be also good to check this variation using different atmosphere assumptions.

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