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High-energy atmospheric muons at sea level

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High-energy atmospheric muons are of special relevance to deep underwater/ice large-volume neutrino telescopes as they constitute by far their major event yield. Understanding their characteristics at sea level can help to properly interpret the observed signal. This work aims to investigate the flux and the charge ratio of atmospheric muons above 100 GeV at sea level. The calculations are carried out using the simulation program CORSIKA in combination with different up-to-date hadronic interaction models. The obtained results are compared with recent experimental data as well as with Gaisser analytical parametric model.

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1. Introduction

Atmospheric muons originate from the interactions of primary cosmic rays with air nuclei in the upper atmosphere. They are mainly produced as decay products of secondary charged pions ($\pi^{\pm}$) and charged kaons ($K^{\pm}$) in the resulting hadronic showers. Most of them occur at high altitudes (typically 15 km) and travel with other particles to the Earth's surface in cascades within a few degrees of the trajectory of the primary particle that creates them. They are very penetrating, making them the most abundant charged particles arriving at sea level with a rate of about 1 muon/cm^2/min above 1 GeV for horizontal detectors, and a mean energy of approximately 4 GeV [1]. They are usually used to study the energy spectrum and elemental composition of primary cosmic rays. They are also of great importance to constrain calculations of the atmospheric neutrino fluxes [2].

Atmospheric muons have been studied for a very long time. In the beginning, measurements were undertaken by means of simple ground-based devices (see, e.g., [3] and references therein). Then, highly sophisticated detectors deployed alongside particle accelerators were used to investigate atmospheric muons underground [4–6]. Underground neutrino experiments have also the opportunity to measure cosmic-ray muons [7–10]. The spectrum at the surface is obtained by correcting for the overburden. Underground detectors offer the advantage of filtering out low-energy particles, hence emphasizing the high-energy part of the muon spectrum.

The present work focuses on atmospheric muons with energies above 100 GeV, which are highly relevant to very large-volume neutrino telescopes like IceCube [11], KM3NeT [12] and Baikal-GVD [13]. Indeed, they are the most frequent particles triggering such deep detectors. A fair knowledge of their properties at sea level can help to properly interpret data observed deep underwater/ice. Furthermore, atmospheric muons with energies above a few hundreds TeV can provide information about the contribution to atmospheric lepton fluxes from the prompt decay of short-lived hadrons [14, 15].

2. Methods

To determine the sea level properties of atmospheric muons above 100 GeV, we carried out a series of detailed Monte Carlo simulations of extensive air showers (EAS) initiated by high-energy cosmic-ray particles. We used for this purpose the comprehensive computer code CORSIKA version 7.7410 [16], in combination with the post-LHC hadronic interaction models EPOS-LHC [17], QGSJET II-04 [18, 19], and SIBYLL 2.3d [20, 21]. We investigated the momentum spectrum of vertical atmospheric muons as well as their charge ratio at sea level.

The characteristics of atmospheric muons depend strongly on the energy spectrum and mass composition of primary cosmic rays. In this regard, we used the phenomenological model of Gaisser-Stanev-Tilav, which is based on the assumption that there are three populations of primary cosmic rays [22]. The first two populations can be associated with acceleration by sources in the Milky Way, while the third population is supposed to be of extragalactic origin. Under this model, each of the three components (j) contains up to five groups of nuclei (p, He, C, O, and Fe) with assumed spectral indices as adjustable parameters, and cuts off exponentially at a characteristic

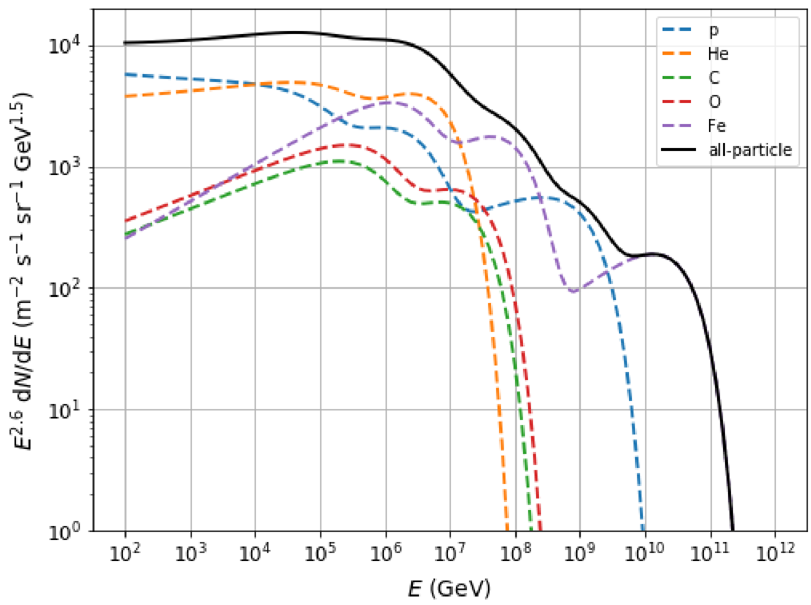

Figure 1: Gaisser-Stanev-Tilav model for the energy spectrum of primary cosmic rays [22].

rigidity $R_{c,j}$. The all-particle primary energy spectrum is then given by

$$\phi_i(E) = \sum_{j=1}^{3} a_{i,j}\ E^{-\gamma_{i,j}}\ \exp\left(-\frac{E}{Z_i R_{c,j}}\right), \tag{1}$$

where E is the primary energy, $\gamma_{i,j}$ is the spectral index, and $a_{i,j}$ is a normalization constant. The subscript i runs over the five groups of nuclei, and the all-particle spectrum is the sum of the five (Figure 1). In order to ensure sufficient statistics at all energies, we first injected particles following E^{-1} up to the maximum energy, and then reweighed the obtained distributions together with the appropriate normalization to match equation (1). We used in each run 10^5 primary cosmic-ray particles between 10^2 and 10^6 GeV.

We set a fictive detector at sea level with a radius equal to approximately the maximum of the lateral distribution of muons. We redistributed the cores of simulated showers randomly over an effective area of a radius equal to twice the detector radius. Thus, about 25% of the simulated muons hit the fictive detector.

3. Momentum spectrum

During the last decades, the atmospheric muon flux and energy/momentum spectrum have been studied by a variety of experiments using different methods [23]. Direct measurements usually involve magnetic spectrometers, where the momentum of each muon is inferred from the curvature of the track left by the muon in the detector. Owing to favorable experimental conditions, measurements at ground/sea level offer the great advantage of high stability, large-collecting areas, and long exposure time.

Figure 2 presents the obtained momentum spectrum of vertical atmospheric muons above 100 GeV at sea level for the different hadronic interaction models. As can be seen, Monte Carlo

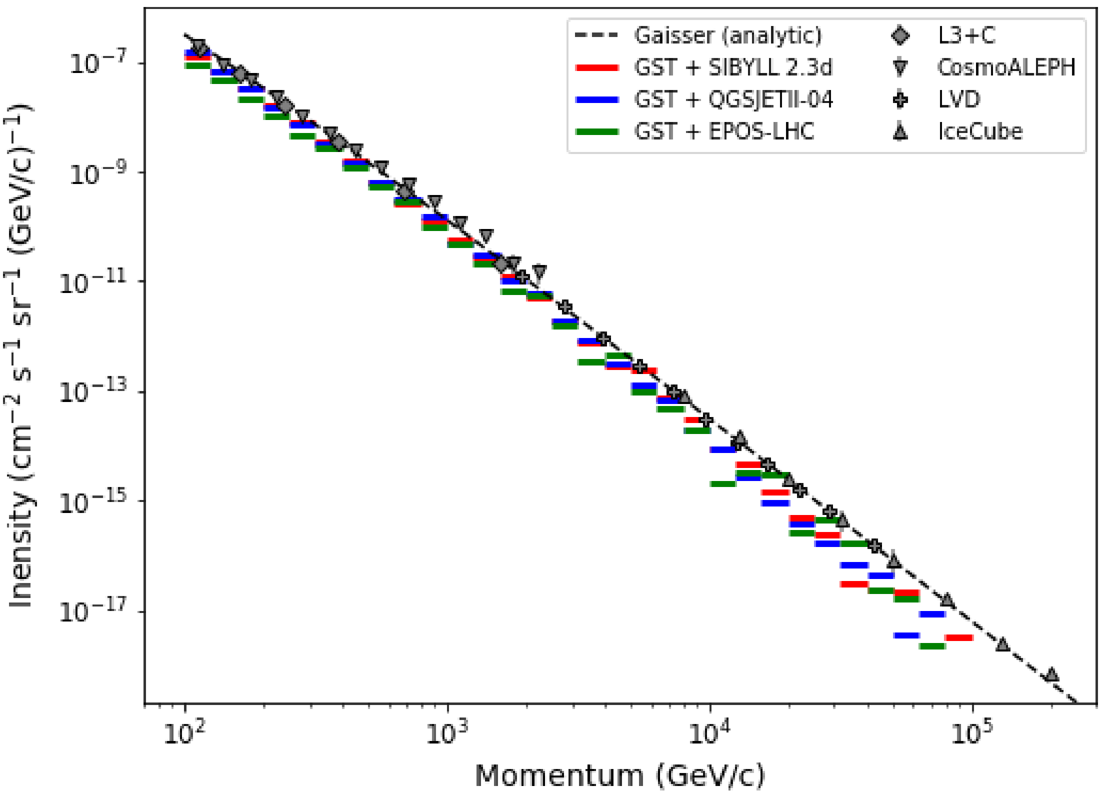

Figure 2: Calculated momentum spectrum of vertical atmospheric muons at sea level as compared with data from L3+C [4], CosmoALEPH [6], LVD [7], and IceCube [10] as well as with Gaisser analytical parametric model [1].

simulations are quite consistent with the experimental data from L3+C [4], CosmoALEPH [6], LVD [7], and IceCube [10]. They also agree fairly with Gaisser analytical parametric model [1], though with an expected small mismatch above approximately 40 TeV due to a lack of statistics. The three hadronic interaction models give almost the same intensity of atmospheric muons at sea level.

4. Charge ratio

The charge ratio of atmospheric muons, i.e. the ratio of fluxes of positive to negative muons (N_μ^+/N_μ^-), is a key quantity that reflects important features of the hadronic interaction and can help to discern the primary mass composition. Most notably, it expresses the excess of π^+ over π^- and K^+ over K^- in the forward fragmentation region of proton induced interactions, in conjunction with the fact that primary cosmic rays are positively charged. An increasing contribution of kaon decays to the muon charge ratio is observed in the TeV energy range [8]. Above 10 GeV, where geomagnetic and solar effects are insignificant, the experimental value of N_μ^+/N_μ^- is found to be nearly constant at about 1.3 [3, 9].

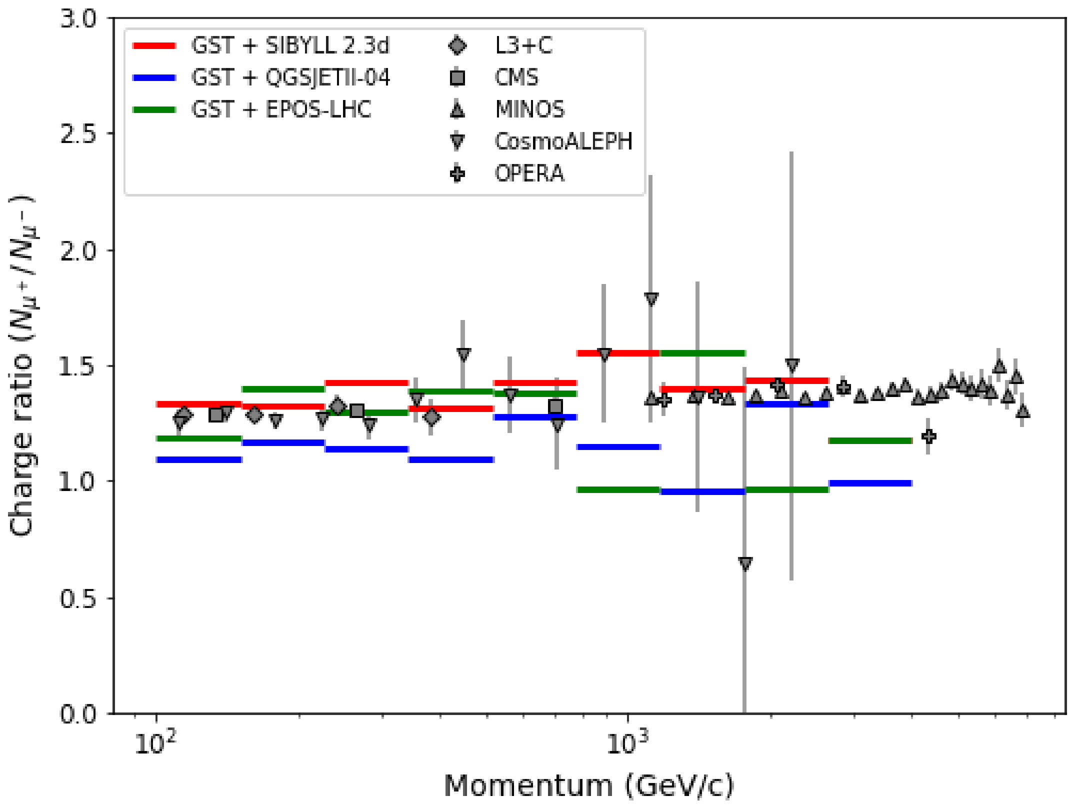

Figure 3: Calculated charge ratio of vertical atmospheric muons at sea level as a function of muon momentum. Also shown are data from L3+C [4], CMS [5], CosmoALEPH [6], MINOS [8], and OPERA [9].

Figure 3 presents the obtained charge ratio of vertical atmospheric muons above 100 GeV at sea level as a function of the muon momentum for the different hadronic interaction models. We notice here that the results are in line with the experimental data from L3+C [4], CMS [5], CosmoALEPH [6], and OPERA [9]. However, above 3 TeV there is a discrepancy of about 15-30% with MINOS data [8]. Moreover, it is worthy to note that QGSJETII-04 model underestimates the charge ratio of vertical muons in comparison with SIBYLL 2.3d and EPOS-LHC.

5. Conclusion

We investigated the main sea-level properties of high-energy atmospheric muons, which are of great relevance to very large-volume neutrino telescopes as they provide the dominant signal deep underwater/ice. In that respect, we carried out elaborate extensive air shower simulations using the program CORSIKA in combination with three different up-to-date hadronic interaction models. We considered in particular the momentum spectrum and the charge ratio of vertical atmospheric muons. The obtained results indicate a good overall agreement with experimental data as well as

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with Gaisser analytical parametric model. However, there are still some small discrepancies at high energy that need further investigation.

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