High energy atmospheric muons at sea level

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Abstract

High-energy atmospheric muons produced in cosmic-ray induced air showers represent by far the major event yield in deep underwater large-volume neutrinos telescopes. A fair knowledge of their characteristics at sea level can help to properly interpret the observed signal. This work aims at investigating the momentum spectrum and charge ratio of vertical atmospheric muons above 100 GeV at sea level. The calculations are carried out using CORSIKA code along with different up-to-date hadronic interaction models. The obtained results are fully in line with experimental data as well as with Gaisser analytical parametric model.

Atmospheric muons

Atmospheric muons result from the interactions of primary cosmic rays with air nuclei in the atmosphere. They are mainly produced as decay products of pions ($\pi^{\pm}$) and kaons ($\mathrm{K}^{\pm}$):

$$\begin{cases} \pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \\ \mathrm{K}^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \end{cases}$$

They are the most abundant charged particles at sea level with an average intensity of [1]

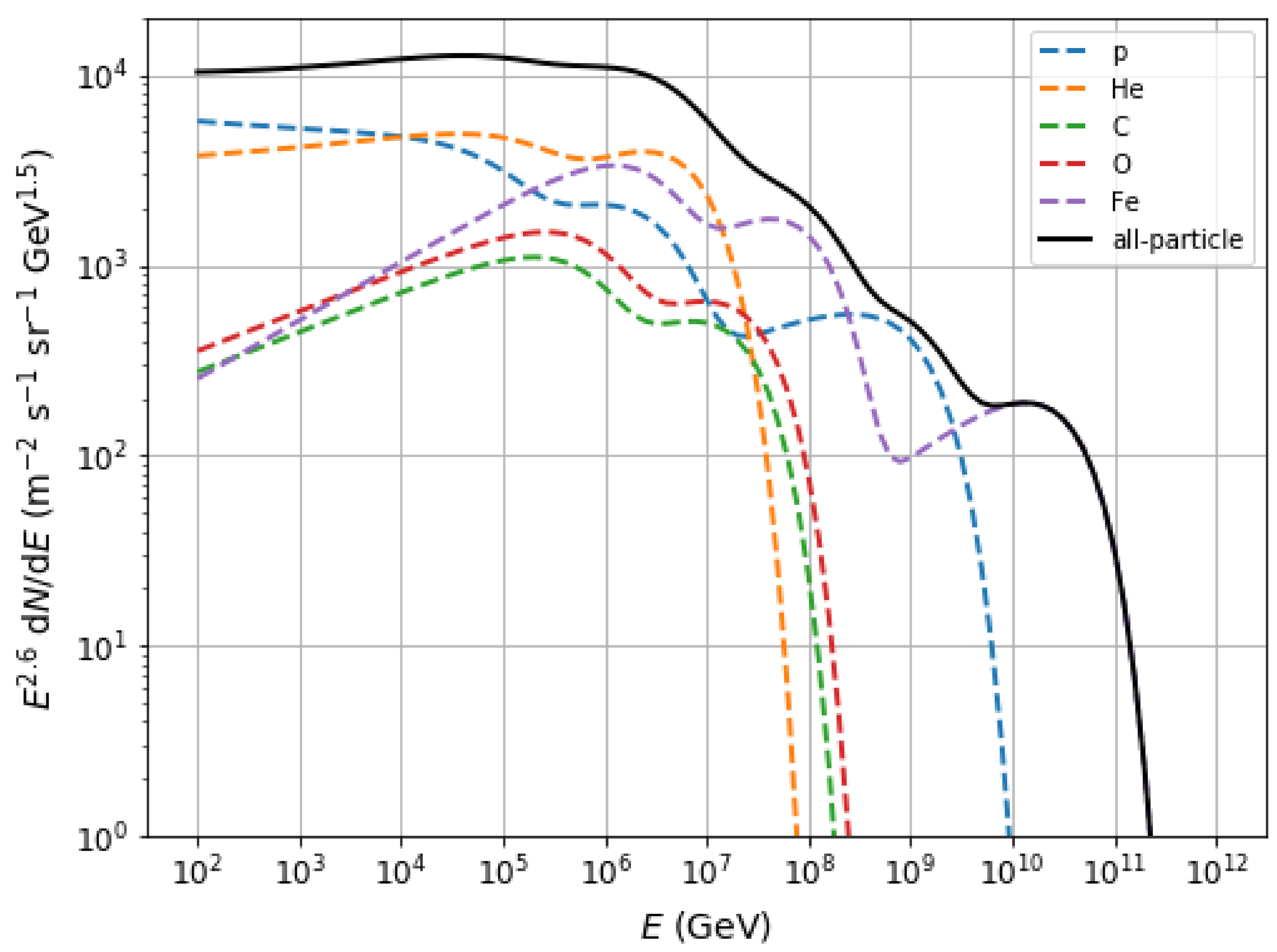
$$I(> 1\ \mathrm{GeV}) \sim 70\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

Atmospheric muons are very penetrating and thus are the most frequent particles triggering deep underwater/ice large-volume neutrino telescopes, such as IceCube, KM3NeT and Baikal-GVD. Understanding their major characteristics at sea level is crucial to correctly interpret the data observed by such detectors.

Methods

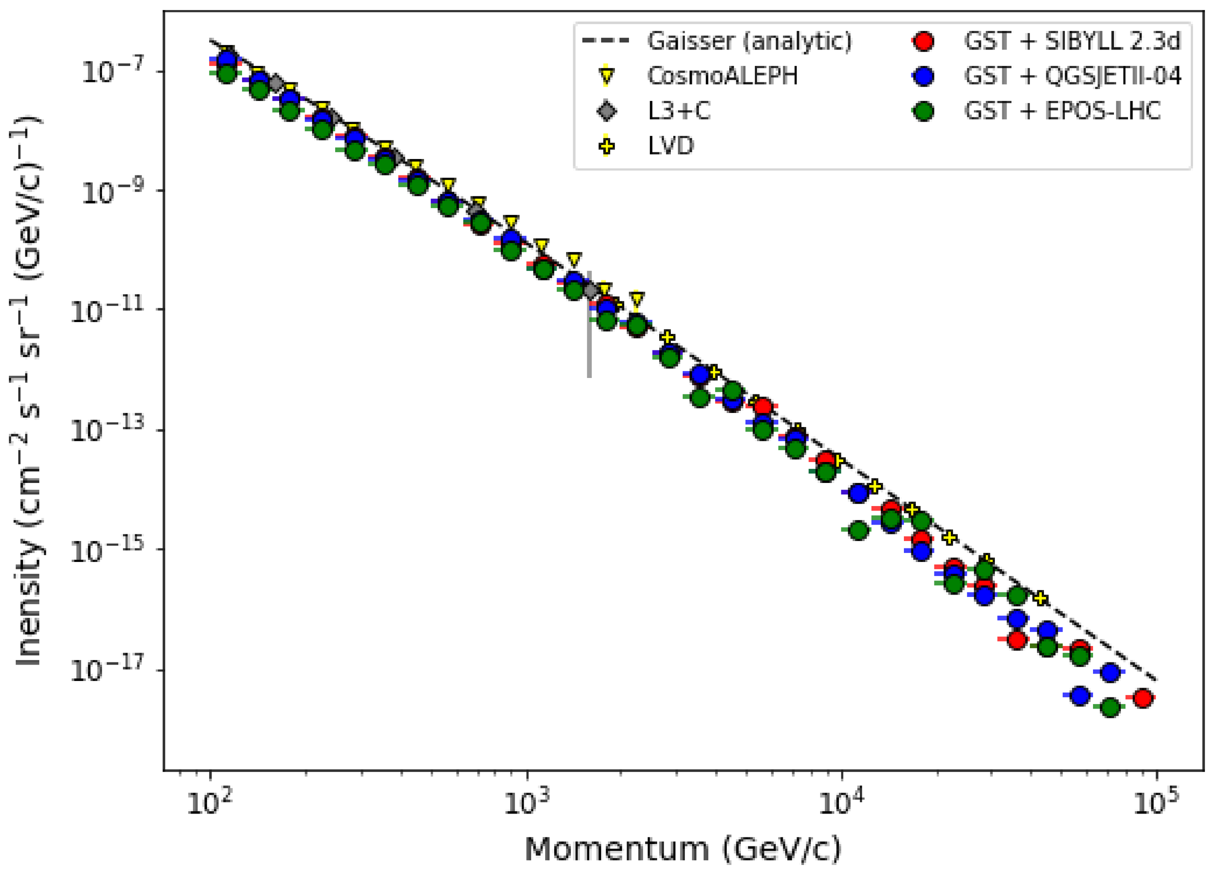
- We simulated extensive air showers using CORSIKA 7.7410 [2], in combination with the post-LHC hadronic interaction models SIBYLL 2.3d [3], QGSJETII-04 [4] and EPOS-LHC [5].
- For the primary spectrum we used Gaisser-Stanev-Tilav (GST) model with 5 groups of primary nuclei (p, α, C, O, Fe) [6].
- The primary energy was first sampled following E^{-1}, then reweighted so as to comply with the GST model.
- We simulated 10^5 vertical air showers per run in the energy range 10^2-10^6 GeV and set the energy cutoff at 100 GeV.
- We set a fictive detector with a radius equal to the maximum of the muon lateral distribution at sea level. We redistributed the cores of simulated showers at random over an effective area of a radius equal to twice the detector radius (efficiency $\sim 25\%$).

Primary cosmic-ray spectrum



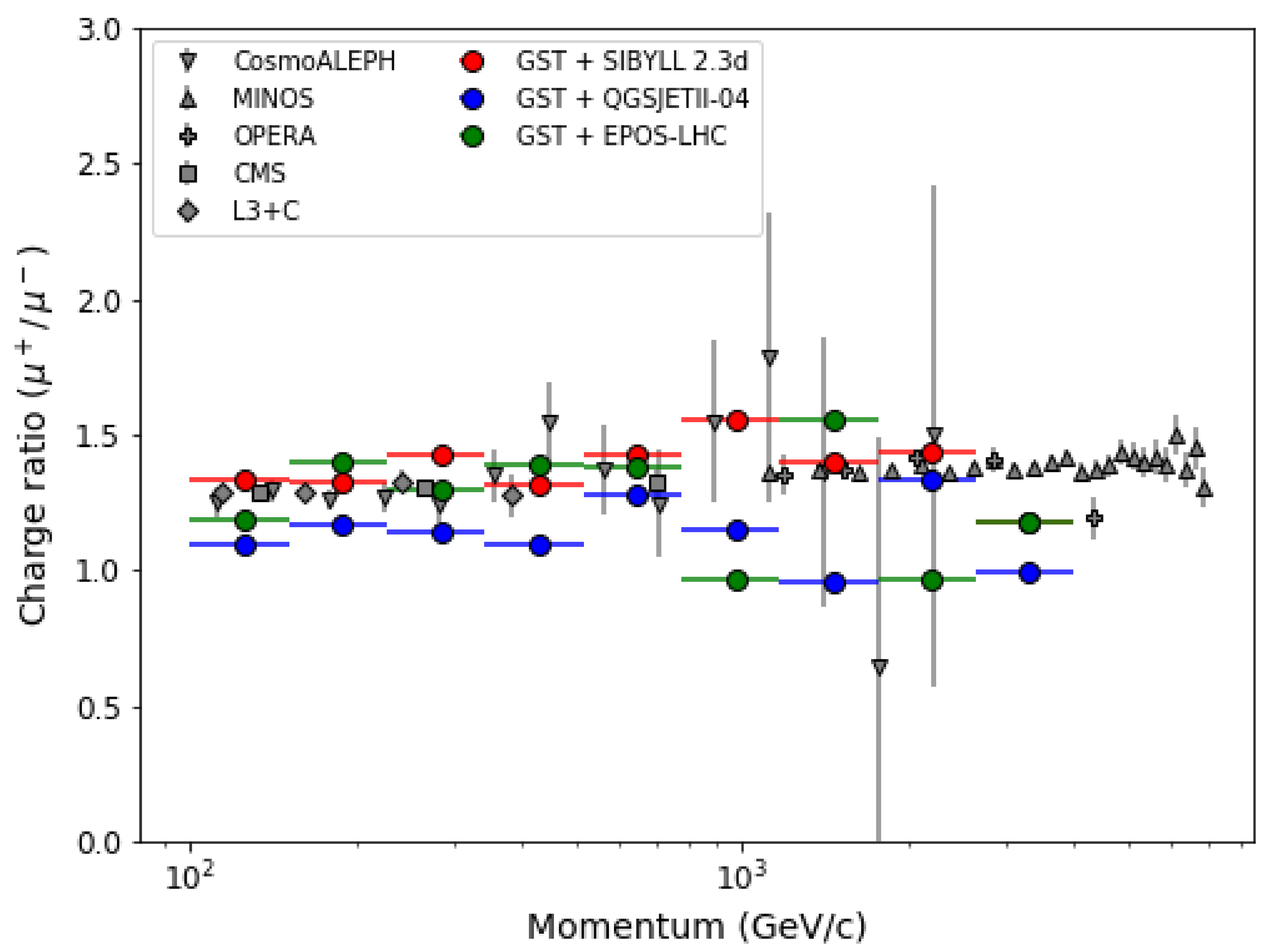
The characteristics of atmospheric muons depend strongly on the energy spectrum and mass composition of primary cosmic rays. The phenomenological model of Gaisser-Stanev-Tilav [6] is based on the assumption that there are three populations of primary cosmic rays. Each of the three components contains 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 rigidity. The all-particle energy spectrum is the sum of the five components (figure above).

Muon momentum spectrum



This figure presents the momentum distribution of vertical atmospheric muons above 100 GeV at sea level. As can be seen, Monte Carlo simulations describe well the experimental data from CosmoALEPH [7], L3+C [8], and LVD [9]. 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.

Muon charge ratio (μ^+/μ^-)



This figure presents the charge ratio of vertical atmospheric muons above 100 GeV at sea level as a function of momentum. This quantity reflects important features of the hadronic interaction and can help to discern the primary mass composition. We notice here that the obtained results agree with the experimental data from CosmoALEPH [7], L3+C [8], CMS [10], and OPERA [11]. However, above 3 TeV there is a discrepancy of about 15-30% with MINOS data [12]. 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.

Conclusion

Monte Carlo simulation of the main properties of vertical high-energy atmospheric muons at sea level, using CORSIKA with three different up-to-date hadronic interaction models, indicates a good overall agreement between the numerical results and the experimental data as well as Gaisser analytical parametric model. However, there are still some small discrepancies at high energy that need further investigation.

References

[1] Particle Data Group, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[2] D. Heck *et al.*, Report FZKA 6019, Forschungszentrum Karlsruhe (1998).
[3] F. Riehn *et al.*, Phys. Rev. D **102**, 063002 (2020).
[4] S. S. Ostapchenko, Phys. Rev. D **83**, 014018 (2011).
[5] T. Pierog *et al.*, Phys. Rev. C **92**, 034906 (2015).
[6] T. K. Gaisser, T. Stanev and S. Tilav, Front. Phys. **8**, 748 (2013).
[7] CosmoALEPH Collaboration, Astropart. Phys. **49**, 1 (2013).
[8] L3 Collaboration, Phys. Lett. B **598**, 15 (2004).
[9] LVD Collaboration, Phys. Rev. D **58**, 092005 (1998).
[10] CMS Collaboration, Phys. Lett. B **692**, 83 (2010).
[11] OPERA Collaboration, Eur. Phys. J. C **67**, 25 (2010).
[12] MINOS Collaboration, Phys. Rev. D **76**, 052003 (2007).