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Analytical description of atmospheric muon spectra at large zenith angles

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Atmospheric muon spectra are used in a range of cosmic-ray studies, including investigations of extensive air showers, atmospheric particle production, and atmospheric neutrino fluxes, as well as for validating particle-transport and cascade models. In particular, the spectrum is critical for estimating matter distribution in muography. For practical applications, compact analytical parameterizations are preferable to computationally demanding Monte Carlo simulations, for example, when optimizing detector configurations or estimating exposure times. However, the accuracy of commonly used parameterizations at large zenith angles remains an important issue. We tested four analytical parameterizations of the differential atmospheric muon energy spectrum - Tang, Shukla, Reyna, and Bogdanova - against an independent experimental database from nine experiments, covering zenith angles from 0° to 90° . None of the considered parameterizations with published parameters provides satisfactory agreement with the experimental data over the full zenith-angle range. By fitting each zenith interval we obtained the systematic angular dependence of the model parameters. This indicates that the existing functional forms do not completely capture the angular dependence of the muon spectrum. These results motivate further development of functional forms or parameterizations with angle-dependent parameters, which could improve the accuracy of atmospheric muon flux for applications. Additional experimental measurements, especially at large zenith angles could also help improve the description of these dependences.

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