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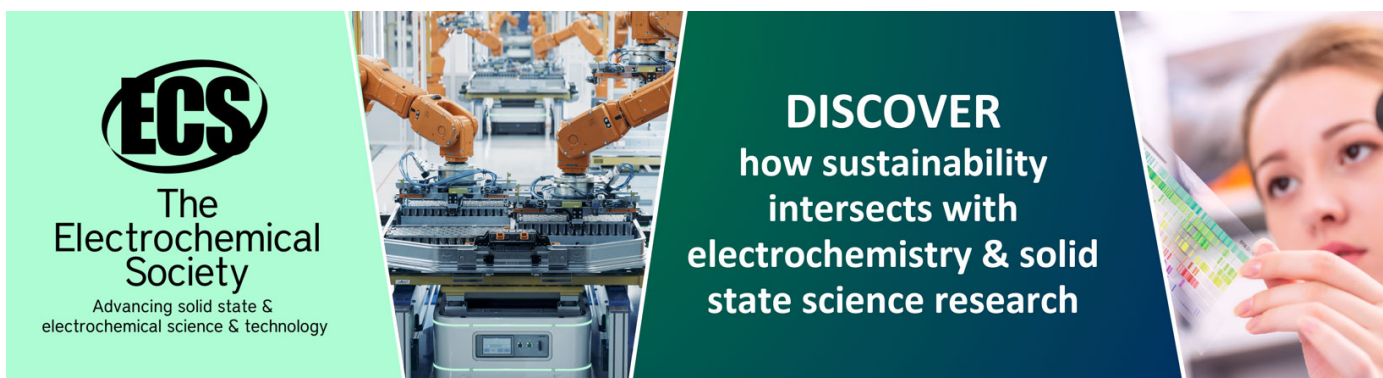
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Testing of the EPOS LHC, QGSJET01, QGSJETII-03 and QGSJETII-04 hadronic interaction models via help of the atmospheric vertical muon spectra

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Abstract. The recent results of the very precise measurements of the primary cosmic protons and helium nuclei energy spectra by AMS-02 and some rather accurate estimates of these energy spectra generated in SNR allow us to elaborate the new approximation of the primary nucleon energy spectra. As the accuracy of this approximation is rather high we can use it to test various models of hadronic interactions with the help of atmospheric muon energy spectra. The atmospheric vertical muon energy spectra have been calculated in terms of the EPOS LHC, QGSJET01, QGSJETII-03 and QGSJETII-04 models in the energy range $10^2 \div 10^5$ GeV with help of the CORSIKA package and this new approximation of the primary nucleon spectrum. The comparison of calculations with the muon spectra observed by collaborations L3+Cosmic, LVD and MACRO has shown that all models predict approximately two times lower intensity of the muon energy spectra. As these muons are products of decays of the most energetic $\pi^\pm$ and $K^\pm$ mesons in the atmosphere, we can conclude that production of these $\pi^\pm$ and $K^\pm$ mesons is underestimated by EPOS LHC, QGSJET01, QGSJETII-03 and QGSJETII-04 models.

1. Introduction

The extensive air showers (EAS) are the only tool to understand the origin and composition of cosmic rays, their possible sources and a mechanism of acceleration.



All features of the energy spectrum, arrival directions and composition of the primary cosmic particles should be determined through an analysis of the EAS data. These data as some signals in the surface and underground detectors are usually interpreted in terms of various models of hadronic interactions [1–9]. It happened, that such interpretation leads to some inconsistency. As an example, energy of showers calculated in terms of the QGSJET II-03 [3] model with help of the surface detectors signals at Telescope Array [10] happened to be 1.27 times larger than this energy estimated with help of the fluorescence light. Usually these models are tested with the help of the accelerator data at small values (~ 0) of the pseudorapidity η where most of secondary particles (mainly mesons) are produced [11–13]. However, calculations have shown that the maximal energy flow carried by secondary particles occurs at much larger values (~ 8 – 10) of the pseudorapidity η [14]. So, it is of the primary importance to verify a production of the most energetic mesons simulated in terms of various models. This verification may be carried out by comparing model predictions of this muon fluxes with data of the classical experiments L3+Cosmic [15], MACRO [16] and LVD [17] in the energy interval of $10^2 - 10^5$ GeV. Showers induced by the primary protons and helium nuclei with different fixed energies have been simulated with help of the CORSIKA package [18] and the muon partial energy spectrum in each individual shower have been calculated. Then a convolution of these simulations for every type of the primary particles with intensities of these particles has been estimated. Inspired by new precision cosmic rays data base [19] (e.g. AMS-02 [20], PAMELA [21], ATIC-2 [22], CREAM [23], ARGO-YBJ [24], ARGO-YBJ & FWCTA [25], KASCADE [26], KASCADE-Grande [27], Tunka [28], IceCube [29], Telescope Array [30]), we suggested new approximations of cosmic ray energy spectra for primary protons and helium nuclei. Besides some calculations of spectra of the primary proton and helium nuclei in SNR [31] should also be used. Thus, with the help of any interaction models [1–9], the package CORSIKA and data on fluxes of the primary cosmic nuclei [20–31] one can predict the energy spectra of atmospheric vertical high energy muons at sea level. These predictions can be compared with data observed by collaborations L3+Cosmic, MACRO and LVD at energies above 100 GeV. In fact, some low energy models with the package FLUKA [32] have been tested in such a way. We are sorry that some our results of models testing in [33–35] are not correct. We do apologize for our mistake in input data for the atmosphere.

In this paper models EPOS LHC [7], QGSJET-01 [1], QGSJET II-03 and QGSJET II-04 [4] have been tested. A comparison of muon data observed in [15–17] with results of simulations allows to draw a conclusion that these models failed to be produce correctly the most energetic mesons.

2. Method

To estimate the energy spectra $D(E_\mu)$ of atmospheric vertical muons in the energy range of $10^2 - 10^5$ GeV we need to know the energy spectra dI_p/dE and dI_{He}/dE of the primary protons and helium nuclei within the energy interval of $10^2 - 10^7$ GeV and the partial energy spectra $S_p(E_\mu, E)$ and $S_{He}(E_\mu, E)$ of the vertical muons in EAS induced by the primary protons and helium nuclei with the various fixed energies E . Simulations of these partial muon spectra have been carried out in terms of the EPOS LHC, QGSJET-01, QGSJET II-03 and QGSJET II-04 hadronic interaction models in the same energy

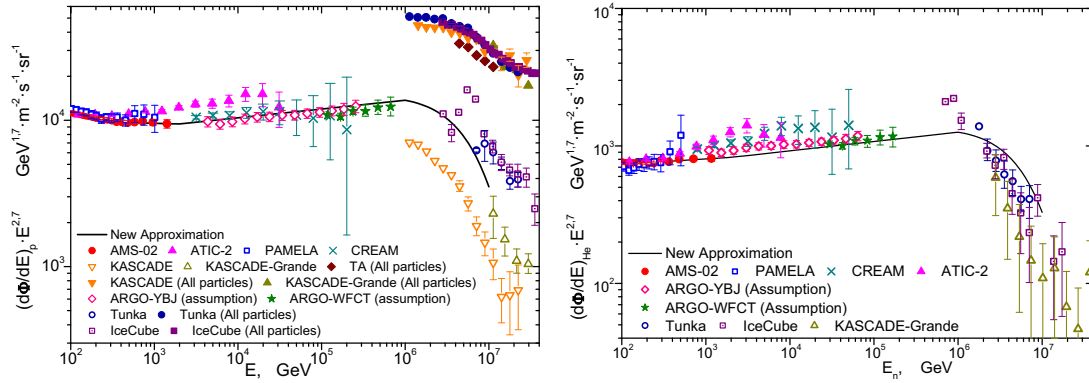


Figure 1. Energy spectra of primary nucleons: protons - left panel, helium - right panel. All particles spectra depends on energy per particle.

range of $10^2 - 10^7$ GeV.

The hypothesis of superposition [36] is also used. As direct results coincides with simulations in terms of the hypothesis of superposition, we will use this hypothesis.

We had used approximations the energy spectra of the primary protons and helium nuclei for (dI_p/dE) and (dI_{He}/dE) suggested in [37]. Figure 1 demonstrate how these approximations fit data [20-30].

The package CORSIKA 7.4 had been used to simulate the second important ingredients - the partial energy spectra $S_p(E_\mu, E)$ and $S_{He}(E_\mu, E)$ of vertical muons in showers induced by the primary protons and helium nuclei with the various fixed energies E .

The results of these calculations in the energy range of $10^2 - 10^7$ GeV were interpolated for 100 values of energies E with equal intervals in decimal logarithmic scale. The energy interval $10^2 - 10^5$ GeV of muons was divided into 60 equal bins also in decimal logarithmic scale. So, the width of the bin was equal to $h = \lg(E_{\mu,(i+1)}/E_{\mu,i}) = 0.05$.

The energy spectra $D_p(E_\mu)$ and $D_{He}(E_\mu)$ of muons for the primary protons and helium nuclei are calculated as integrals of products of functions $S_p(E_\mu, E)$ and $S_{He}(E_\mu, E)$ with corresponding intensities dI_p/dE and dI_{He}/dE of the primary protons, on energy E of primary nucleons.

$$D_p(E_\mu) = \int \left(\frac{dI_p}{dE} \right) \cdot S_p(E_\mu, E) \cdot dE \quad (1)$$

$$D_{He}(E_\mu) = \int \left(\frac{dI_{He}}{dE} \right) \cdot S_{He}(E_\mu, E) \cdot dE \quad (2)$$

Resulting energy spectrum of atmospheric muons is the sum of these energy spectra of muons produced by primary protons and helium nuclei.

$$D(E_\mu) = D_p(E_\mu) + D_{He}(E_\mu) \quad (3)$$

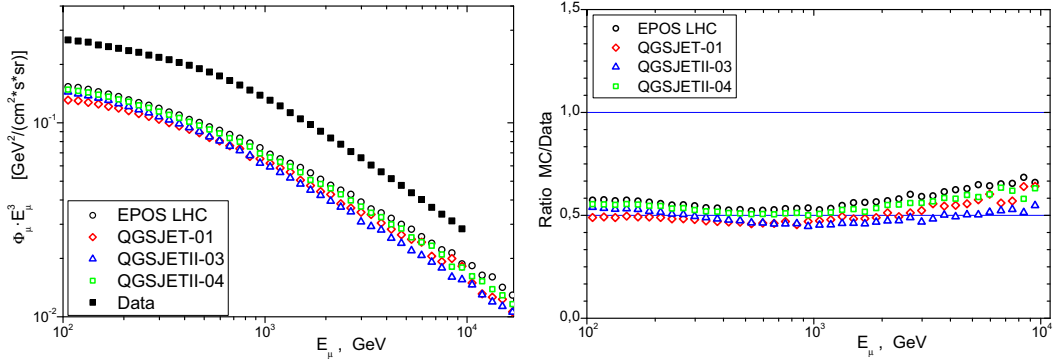


Figure 2. The energy spectra of near vertical muons - left panel. The ratio MC/DATA - right panel.

3. Results of simulations

The partial energy spectra $S_p(E_\mu, E)$ of the atmospheric vertical muons have been simulated for various fixed energies E of the primary protons in terms of the EPOS LHC, QGSJET-01, QGSJET II-03 and QGSJET II-04 models with statistics of $\sim 10^6$. It happened that this statistics end of the spectra is not enough and additional simulations with statistics 10^7 have been carried out.

We compared the total number of muons with energies above 10² and 10³ GeV in showers induced by the primary protons with energies 10⁵ and 10⁶ GeV estimated in terms of the these models in our simulations and in [38]. The very reasonable agreement has been found.

The final results of the muon energy spectra $D(E_\mu)$ calculated in terms of the EPOS LHC, QGSJET-01, QGSJET II-03 and QGSJET II-04 models and data [15-17] are shown in figure 2 (left panel) and ratios of MC simulation to data - in the same figure (right panel). It is seen that calculated spectra are ~ 2 times below data in case of the QGSJET II-03 model and ~ 1.7 times below data for the EPOS LHC model. The result of the rest of models are in between of these limits. The main conclusion is quite clear. All considered models demonstrate the valuable deficit of muons.

4. Conclusion

Muons are produced in decays of the most energetic $\pi^\pm$ -mesons and $K^\pm$ -mesons generated in first interactions of the primary particles with nuclei in the atmosphere.

As calculated vertical muon energy spectra in case of the EPOS LHC, QGSJET-01, QGSJET II-03 and QGSJET II-04 models are $\sim 1.7 \div 2$ times below data we can conclude that production of the most energetic $\pi^\pm$ -mesons and $K^\pm$ -mesons in these models is considerably suppressed. This suppression may induce smaller values of signals in the surface scintillation detectors and will result in larger values of the calculated energy estimates. So, the coefficient 1.27 used by the TA collaboration [10] may be understood as a result of this suppression. The increased intensity of the primary particle flux observed at the Yakutsk array at super high energies [39] may be also a result of smaller values of calculated signals in surface scintillation detectors.

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