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Testing of the DPMJET and VENUS hadronic interaction models with help of the atmospheric muons

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Abstract. The more accurate original calculations of the atmospheric vertical muon energy spectra at energies 10^2 - 10^5 GeV have been carried out in terms of DPMJET and VENUS models. The Gaisser-Honda approximations of the measured energy spectra of primary protons, helium and nitrogen nuclei have been used. The package CORSIKA has been used to simulate cascades in the standard atmosphere induced by different primary particles with various fixed energies E. Statistics of simulated cascades for secondary particles with energies $(0.01-1)\cdot E$ was increased up to 10^6. It has been shown that predictions of the DPMJET and VENUS models for these muon fluxes are below the data of the classical experiments L3 + Cosmic, MACRO and LVD by factors of $\sim$ 1.6-1.95 at energies above 10^2 GeV. It has been concluded that these tested models underestimate the production of the most energetic secondary particles, namely, π-mesons and K-mesons, in interactions of the primary protons and other primary nuclei with nuclei in the atmosphere by the same factors.

1. Introduction

The extensive air showers (EAS) data as some signals in the surface and underground detectors are usually interpreted in terms of various models of hadronic interactions [1-8]. Such interpretation may be not obligatory correct. As an example, energy of showers calculated in terms of the QGSJETII-03 [2] model with help of the surface detectors signals at TA [9] happened to be 1.27 times lager than such energy estimated with help of the fluorescence light. To be sure that results of such interpretation are as accurate as possible these models should be thoroughly tested. Usually these models are tested with the help of the accelerator data at small values ($\sim$0) of the pseudorapidity η where most of secondary particles are produced [10-12]. However, calculations have shown that the maximal energy flow carried by secondary particles occurs at much larger values ($\sim$8-10) of the pseudorapidity η [13]. So, it is of the primary importance to verify a production of the most energetic secondary particles simulated in terms of these models. The atmospheric muon flux also depends strongly on such production. So, it is valuable suggestion to test various models of hadronic interactions by comparing model predictions of this muon fluxes with data. For a comparison we select the classical experiments L3+Cosmic [14], MACRO [15] and LVD [16]. The CORSIKA package [17] had been used to calculate the muon energy spectrum in each individual shower. Results of many measurements (e.g. ATIC-2 [18, 19], CREAM [20], RUNJOB [21], AMS02 [22, 23], PAMELA [24]) of the fluxes of the primary cosmic nuclei may be used in simulations. We will use the Gaisser-Honda approximations [25] for energy spectra of the various primary nuclei.

In fact, some low energy models have been tested in such a way with the package FLUKA [26]. We are sorry that our testing of some models in [25-27] are not correct. We do apologize for our mistake in input data for the atmosphere!

In this paper models DPMJET 2.55 [7] and VENUS 4.12 [8] have been tested. A comparison of muon data observed in [14-16] with results of simulations allows to draw a conclusion about the most energetic secondary particle production described by these models.

2. Method

The energy spectra $D(E_\mu)$ of atmospheric vertical muons are estimated in the energy range of 10^2-10^5 GeV. As ingredients we need to know the energy spectra dI_p/dE, dI_{He}/dE and dI_N/dE of the primary protons, helium and nitrogen nuclei within the energy interval $10^2 - 10^7$ GeV and the energy spectra of the vertical muons $S_p(E_\mu, E)$, $S_{He}(E_\mu, E)$ and $S_N(E_\mu, E)$ calculated from the primary protons, helium and nitrogen nuclei with the various fixed energies E in terms of the DPMJET 2.55 and VENUS 4.12 hadronic interaction models in the same energy range of $10^2 - 10^5$ GeV. The smooth approximation of the atmospheric muon data observed by the collaborations L3+Cosmic, MACRO and LVD had been used for comparison with results of simulations.

The energy spectra of the primary particles are important ingredients of simulations. As the energy per nucleon is of importance only the energy spectra of the primary protons, helium and nitrogen nuclei should be taken into account. We had used approximations (1) for $(dI_p/dE)_{GH}$, $(dI_{He}/dE)_{GH}$ and $(dI_N/dE)_{GH}$ suggested by Gaisser and Honda.

We have taken into account a change of primary spectrum above the "knee". At energies above $E_1 = 3 \cdot 10^6$ GeV for the primary protons and above $E_2 = 6 \cdot 10^6$ GeV for the primary helium and nitrogen nuclei we had used modified GH approximations (2) of the energy spectra of primary particles. The values of parameters for Gaisser-Honda approximation are listed in table 1. The approximation parameters α, b and c are dimensionless and K has dimensionality as $[1/(GeV \cdot m^2 \cdot s \cdot sr)]$. The E_k is kinetic energy per nucleon in GeV.

Table 1. Parameters for the Gaisser-Honda approximation.

Nuclei	A	α	K	b	c
H	1	2,74	14900	2,15	0,21
He	4	2,64	600	1,25	0,14
N	14	2,6	33,2	0,97	0,01

$$\frac{dN}{dE_k} = K \cdot \left(E_k + b \cdot exp\left(-c \cdot \sqrt{E_k}\right)\right)^{-\alpha} \quad (1)$$

$$\frac{dN}{dE_k} = K \cdot \left(E_k + b \cdot exp\left(-c \cdot \sqrt{E_k}\right)\right)^{-\alpha} \cdot \sqrt{\frac{E_i}{E_k}} \tag{2}$$

The package CORSIKA 7.4 (and CORSIKA 6.9 in case of the DPMJET model) had been used to simulate the second important ingredients - the energy spectra $S_p(E_\mu, E)$, of vertical muons in the energy range of $10^2 - 10^5$ GeV with statistics 10^6 events for the most energetic muons in showers induced by the primary protons with the various fixed energies E in terms of the DPMJET 2.55 and VENUS 4.12 hadronic interaction models.

Functions $S_p(E_\mu, E)$ were calculated for 24 values of the energy E of the primary protons. 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 $h = \lg(E_{\mu,(i+1)}/E_{\mu,i}) = 0,05$. Let us note that average muon energies for the 1-st, 21-st and 41-st bins we will use later are equal to 105.9, $1.059 \cdot 10^3$ and $1.059 \cdot 10^4$ GeV accordingly. Simulations of $S_{He}(E_\mu, E)$ and $S_N(E_\mu, E)$ for helium and nitrogen nuclei have been carried out only for energies 10^4 and 10^6 GeV to test the hypothesis of superposition [30]. Due to this hypothesis for a nucleus with atomic number A: $S_A(E_\mu, E_A) = A \cdot S_p(E_\mu, E_A/A)$. As results of simulations for the primary nuclei showed a good agreement with this hypothesis we had used this hypothesis to estimate the flux of the nucleons from the primary helium and nitrogen nuclei.

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

$$D_p(E_\mu) = \int \left(\frac{dI_p}{dE}\right) \cdot S_p(E_\mu, E) \cdot dE \tag{3}$$

$$D_{He}(E_\mu) = \int \left(\frac{dI_{He}}{dE}\right) \cdot S_{He}(E_\mu, E) \cdot dE \tag{4}$$

$$D_N(E_\mu) = \int \left(\frac{dI_N}{dE}\right) \cdot S_N(E_\mu, E) \cdot dE \tag{5}$$

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

$$D(E_\mu) = D_p(E_\mu) + D_{He}(E_\mu) + D_N(E_\mu) \tag{6}$$

3. Results of simulations

The energy spectra $S_p(E_\mu, E)$ of the atmospheric vertical muons simulated for various fixed energies E of the primary protons in terms of the DPMJET 2.55 and VENUS 4.12 hadronic interaction models are shown in figures 1 and 2 accordingly. It is seen that statistics of $\sim 10^6$ at the higher energy end of the spectra is not enough.

Table 2 displays the total number of muons with energies above 10^2 and 10^3 GeV in showers induced by the primary protons with energies 10^5 and 10^6 GeV estimated in terms of the DPMJET 2.55 and VENUS 4.12 hadronic interaction models in our simulations and in [31]. The very reasonable agreement is seen.

The next figure 3 demonstrates a comparison of the muon energy spectra $S_p(E_\mu, E)$ calculated in terms of the DPMJET 2.55 model as open triangles (vertex down) and the VENUS 4.12 model as stars for the fixed energy $E = 10^5$ GeV of the primary protons. The results for the DPMJET 2.55 are 30 % below the VENUS 4.12 values at $E_\mu = 10^2$ GeV. This difference is disappearing as energy E_μ is increasing up to 10^4 GeV.

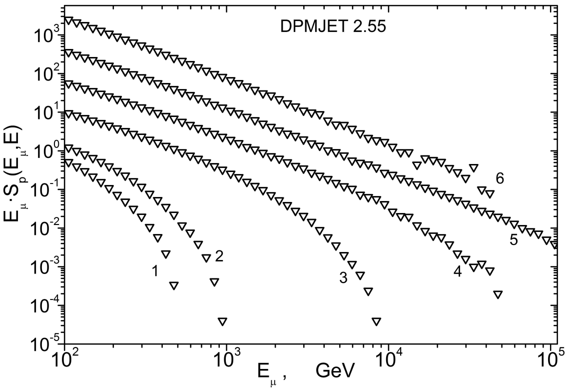

Figure 1. The energy spectra of muons in showers induced by primary protons with various fixed energies E (DPMJET 2.55 model): 1 - $5 \cdot 10^2$; 2 - 10^3; 3 - 10^4; 4 - 10^5; 5 - 10^6; 6 - 10^7 GeV.

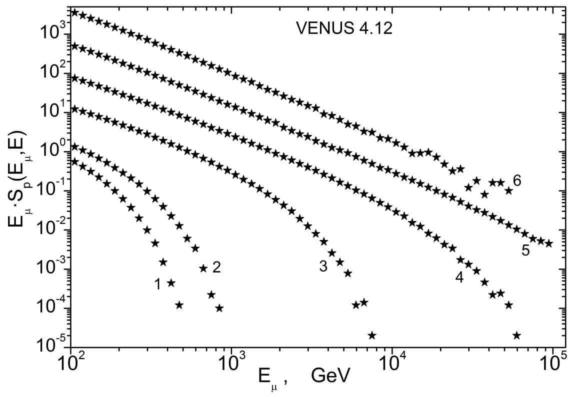

Figure 2. The energy spectra of muons in showers induced by primary protons with various fixed energies E (VENUS 4.12 model): 1 - $5 \cdot 10^2$; 2 - 10^3; 3 - 10^4; 4 - 10^5; 5 - 10^6; 6 - 10^7 GeV.

Table 2. Average number of muons with energies above the threshold E_{th} in showers induced by primary protons with energies E.

	$E = 10^5$ GeV			$E = 10^6$ GeV		
Model	Paper E_{th}	100 GeV	1000 GeV	Paper E_{th}	100 GeV	1000 GeV
VENUS 4.12	[31]	23,5	0,679	[31]	153,5	3,932
VENUS 4.12	This work	24,5	0,652	This work	156,2	3,839
DPMJET 2.55	This work	18,7	0,538	This work	116,7	3,150

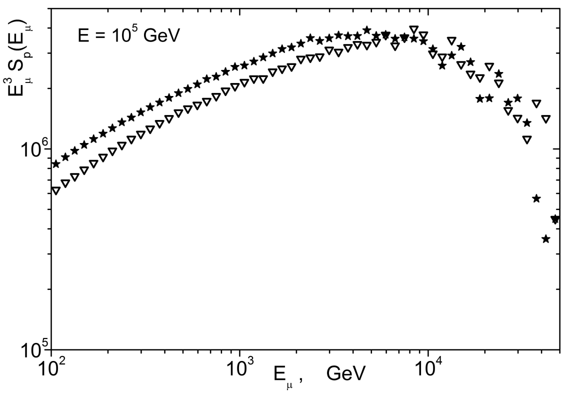

Figure 3. The energy spectra of muons in showers induced by primary protons with fixed energy E = 10^5 GeV. $\bigtriangledown$ - DPMJET 2.55, $\star$ - VENUS 4.12.

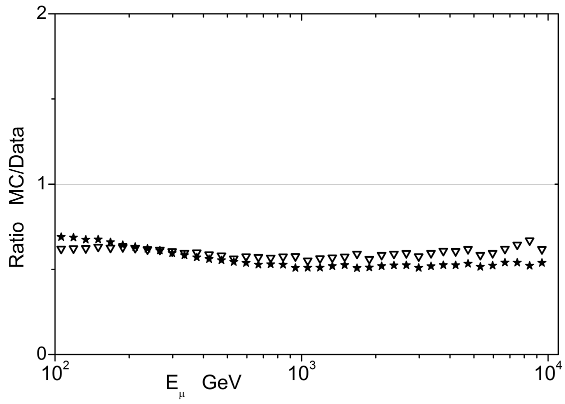

Figure 4. The ratio MC/DATA: $\bigtriangledown$ - DPMJET 2.55 , $\star$ - VENUS.

The results of comparison of calculated in terms of the DPMJET 2.55 and VENUS 4.12 models spectra $D(E_\mu)$ with the smooth approximation of data [14-16] are illustrated in figure 4.

In case of the DPMJET 2.55 model this ratio changes within the interval $55 - 63$ % while in case of the VENUS 4.12 model this ratio decreases from 69% at $E_\mu = 10^2$ GeV up to 52% at $E_\mu = 10^4$ GeV.

4. Conclusion

Muons which contributes much to the muon energy spectra are produced in decays of the most energetic π-mesons and K-mesons generated in first interactions of the primary particles with nuclei in the atmosphere. As calculated vertical muon energy spectra in case of the DPMJET 2.55 and VENUS 4.12 models are 1.60 times and 1.95 times accordingly below data we can conclude that production of the most energetic π-mesons and K-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 [9] to decrease the energy estimates of showers calculated on the base of signals in the scintillation detectors 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 [32] may be also a result of smaller values of calculated signals in surface scintillation detectors.

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