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On the energy spectrum of cosmic ray muons in 100 TeV region

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Abstract. The energy spectrum of cosmic ray muons in the energy range from several TeV to ~ 1 PeV obtained by means of the analysis of multiple interactions of muons (pair meter technique) in the Baksan underground scintillation telescope is presented. Some evidence for the additional muon flux (to the conventional one from pion and kaon decays) has been obtained at energies ~ 100 TeV.

1 Introduction

In the present work we investigate the energy spectrum of cosmic ray muons in 100 TeV region. To do this we use the Baksan underground scintillation telescope (BUST) as 4-layers calorimeter and analyze the events with twofold muon interactions.

2 Application of method of multiple interactions in BUST

In order to evaluate individual muon energies (assuming that they have a power type integral spectrum $\sim E_\mu^{-2.7}$) by means of the pair meter technique (Kokoulin and Petrukhin, 1988) with a reasonable accuracy, it is necessary to detect several (≥ 5) muon interactions in the setup with total target thickness of several hundred radiation length and ~ 100 detecting layers. If the number of layers and the setup thickness are low, the pair meter technique turns into the method of multiple (in a limiting case, twofold) interactions. In this situation, evaluation of energies of individual muons is practically impossible; however, energy characteristics of the muon flux may be investigated on a statistical basis. The sensitivity of such method depends on the shape of muon energy spectrum and, as estimates show, for the conventional or a flatter spectrum, it is sufficient to detect only two interactions even in the setup with the thickness of the order of several tens radiation length.

The BUST (Alexeyev et al., 1979) has four horizontal scintillation planes (which are located one above the other). This allows distinctively select not more than two interactions of muon in the telescope. In the longitudinal profile of energy depositions (in four horizontal planes) in such events, a minimum ("deep", $E_{\rm min}$) in one of the inner planes and two maximums ("humps") above and below it must be observed. It is convenient to denote as E_1 the energy deposition measured in the higher maximum, E_2 the deposition in the second one; then the depth of the deep may be characterized by the ratio $K_2 = E_2/E_{\rm min}$. Simulation of the BUST response for passage of single muons was performed by means of Geant4 toolkit (Agostinelli et al., 2003). The number of simulated events for muon energies above 350 GeV (at ground surface) was comparable to the expected number of such muons for the observation period, and for energies more than 1 TeV, 10 TeV, and 100 TeV exceeded the expected muon statistics in about 5, 40, and 500 times, respectively. In every simulated event, information on energy depositions in scintillation detectors and on muon interactions with energy transfers more than 1 GeV was recorded. We have also performed the BUST response simulation (CORSIKA + Geant4) for EAS muons produced by primary protons with energy $E_o \geq 3 * 10^{15}$ eV and the differential spectrum exponent $\gamma + 1 = 3.1$ (after the "knee").

To estimate muon energy in the pair meter technique, we use rank statistics of energies transferred in muon interactions: transferred energies ε_j (in each event) are arranged in a decreasing order, and the n-th energy value ε_n is then used to estimate muon energy (Kokoulin and Petrukhin, 1988). Since the spectra of rank statistics are nearly similar to the spectrum of muons, it is expedient to use for the following analysis the distributions of events in the value of E_2,

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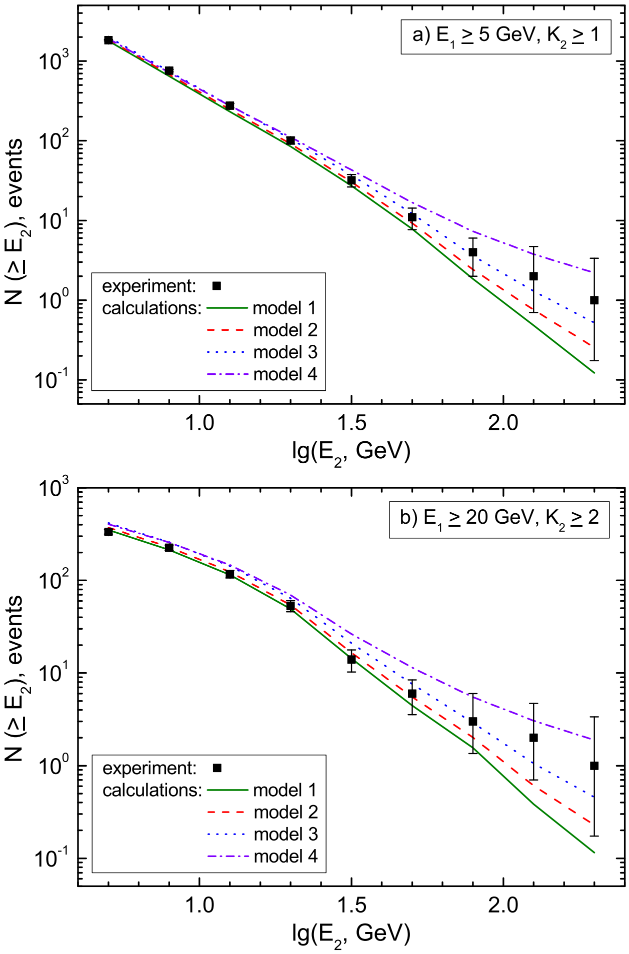

Fig. 1. Integral distributions of experimental events (the points) and expected spectra (the curves) in E_2 for 4 different muon spectrum models (see the text) and two sets of selection criteria (a,b).

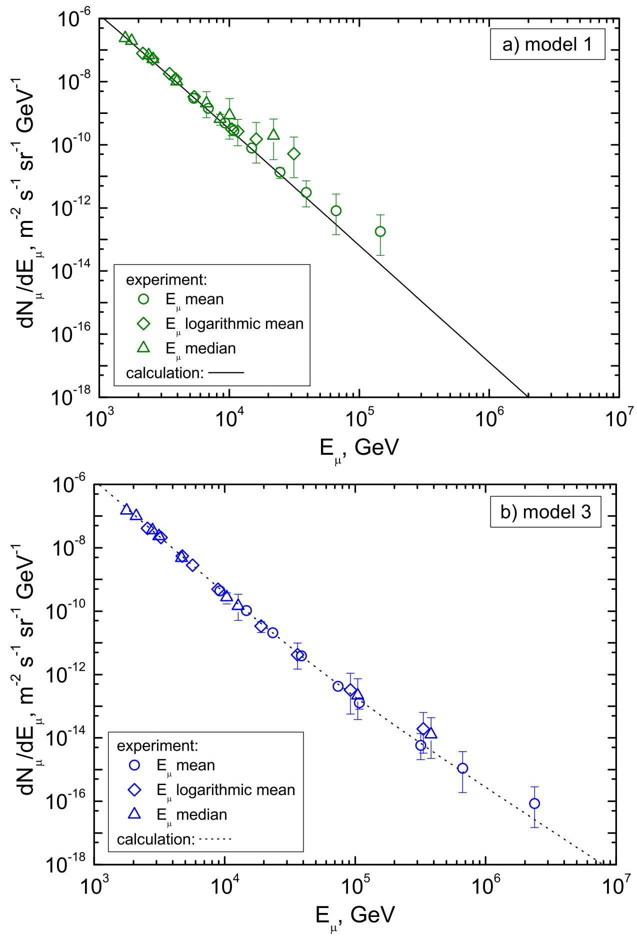

Fig. 2. Differential muon energy spectra reconstructed from BUST data on multiple interactions at different assumptions on muon spectrum model with different choice of effective muon energy: mean (circles), logarithmic mean (diamonds), and median (triangles)

and to vary other parameters of event selection: $E_1 (\geq 5\,\text{GeV}, \geq 20\,\text{GeV}, \geq 40\,\text{GeV}$, etc.) and K_2 ($\geq$ 1, 2, 5, ...).

3 Analysis of experimental data on multiple interactions of muons

Experimental data accumulated during 12.5 years have been analyzed. The total "live" time of registration amounted to 3.3×10^8 s, and the total number of events after preliminary selection (with total energy deposition ≥ 10 GeV in horizontal planes of the BUST) was about 10 millions. In more details, event selection criteria are described in Bogdanov et al. (2009). Only information of horizontal planes was used. The total number of experimental events with twofold muon interactions selected with conditions $E_1, E_2 \geq 5$ GeV and muon tracks crossing all four horizontal planes equals to 1831; the corresponding statistics of simulated events amounts to 27.5 thousand events.

Experimental distributions of the events $N(E_2)$ were compared with Geant4 simulation results for different selection criteria ($E_1 \geq 5$ GeV and $K_2 \geq 1$; $E_1 \geq 20$ GeV and $K_2 \geq 2$, etc.) and four different muon energy spectrum models (R is the ratio of the number of prompt muons to the number of charged pions with the same energy at production):
1. conventional muon spectrum from π-, K-decays in the atmosphere with $R = 0$ and $\gamma_\mu = 2.7$;
2. conventional spectrum with addition of prompt muons at the level of $R = 1 \times 10^{-3}$;
3. the same, but with three times higher prompt muon contribution, $R = 3 \times 10^{-3}$;
4. conventional spectrum with inclusion of very high energy (VHE) muons, which can be produced in hypothetical processes at energies $E > 10^{15}$ eV (see e.g. Bogdanov et al., 2009).

Experimental and calculated integral distributions of the events in E_2 are presented in Fig. 1.

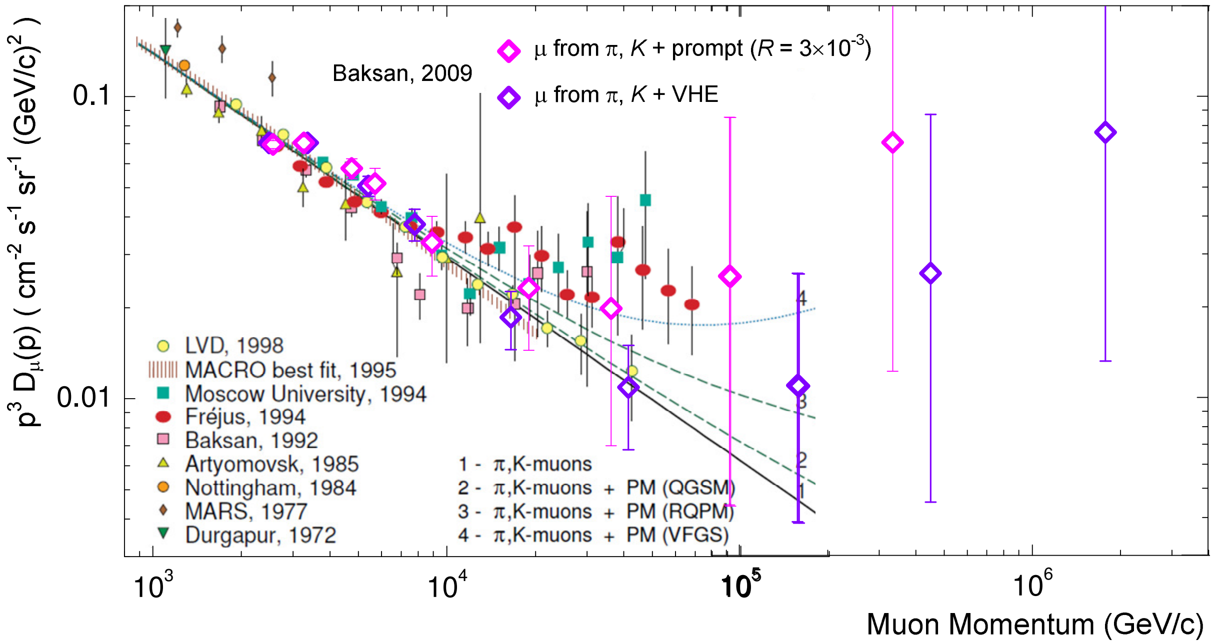

Fig. 3. Differential muon energy spectra for vertical direction measured in various experiments (compilation from Bugaev et al., 1998). The curves are expected fluxes obtained in frame of quark-gluon string model (the curve 2), recombination quark-parton model (3) (Bugaev et al., 1998) and semiempirical model (4) (Volkova et al., 1987). BUST results obtained by means of multiple interaction method are added (open diamonds).

Within statistical uncertainties the data and calculations for a conventional muon spectrum are in a good agreement in the range $5\,\mathrm{GeV} \leq E_2 \leq 30\,\mathrm{GeV}$. However, at large values of E_2 (more than 80 GeV) the expected number of events is several times less than the observed one in the experiment ($\chi^2 = 32.9$ for spectrum model 1 and $\chi^2 = 17.4$ for model 3 at 8 degrees of freedom). It is important to note that the observed excess of events with large values of E_2 is retained at different approaches to data analysis and different selection criteria (compare Fig. 1**(a)** and **(b)**).

The estimates of differential muon spectra N_μ^* are found in a following way:

$$dN_\mu^*(E_\mu^*)/dE_\mu = dN_\mu(E_\mu^*)/dE_\mu \times N_{exp}^{dif}(E_2)/N_{mod}^{dif}(E_2), \quad (1)$$

where $dN_\mu(E_\mu^*)/dE_\mu$ are differential muon energy spectra for the respective spectrum model calculated at corresponding effective muon energy E_μ^* (N_{mod} is the number of simulated events).

Muon energy spectra for vertical direction reconstructed from experimental data at two different assumptions on muon spectrum model are presented in Fig. 2. Results are shown for the selection criterion with highest statistics ($E_1 \geq 5\,\mathrm{GeV}$, $K_2 \geq 1$). Since there is no generally accepted definition of the effective energy of muons responsible for the observed events, the points corresponding to all three versions (mean, logarithmic mean, and median energies) are given in the figure. The curves in each frame represent the assumed spectrum models.

The following conclusions can be made from the analysis of the results presented in Fig. 2. If one assumes that the muon spectrum is formed only due to decays of pions and kaons in the atmosphere (Fig. 2**(a)**), then a strong dependence of spectrum reconstruction results on the choice of the effective muon energy (mean, logarithmic mean, median energy) appears as a large spread of reconstructed points. Furthermore, muon intensity estimated in frame of this assumption in the range of several tens TeV (considering median or logarithmic mean energy) or around 100 TeV (according to mean energy) is practically ten times higher than the expected one and seriously contradicts other experiments. The spread of experimental points relative to the model spectrum curves decreases when the contribution of additional muon flux with a more hard energy spectrum increases (Fig. 2**(b)**). At the same time, the agreement is improving also in the range of moderate muon energies (tens TeV).

In Fig. 3, the differential muon energy spectrum obtained from the BUST data (effective muon energy is logarithmic mean energy) by means of multiple interaction method is compared with the data of other experiments taken from the compilation (Bugaev et al., 1998).

4 Conclusions

The method of multiple interactions of muons based on the ideas of the pair meter technique gives a possibility to use the BUST data for estimation of the energy spectrum of cosmic ray muons in a wide energy region from several TeV to hundreds TeV. The analysis shows that no serious deviations from the conventional spectrum formed as a result of pion and kaon decays are observed up to muon energies $\sim 40-50$ TeV, if the existence of an additional flux of muons with a more hard spectrum is taken into account. At energies > 100 TeV this additional flux may be explained with $R \simeq 3 \times 10^{-3}$.

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