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Muon puzzle in cosmic ray experiments and its possible solution

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ABSTRACT

The term “muon puzzle” was formulated at International Symposium on Future Directions in UHECR Physics in CERN 13–16 February 2012. In this paper, various aspects of muon puzzle are considered. Obtained experimental data can be divided into two types: muon bundle excess compared to simulations which is increasing with the increase of primary particle energy, and the excess of very-high-energy muons (>100 TeV) in the muon energy spectrum. One of the possible (and realistic) solutions of the muon puzzle is the hypothesis about production of blobs of quark-gluon matter with large orbital momentum in nucleus–nucleus interactions at energies more than several PeV. Possibilities of the check of this hypothesis are discussed.

1. Introduction

The beginning of LHC experiments stimulated the interest to possible observations of any phenomenon of new physics. The discovery of the Higgs boson, in fact, has completed construction of the Standard Model, and questions about directions of the next steps to search for new physics appear. In this connection, it is important to analyze cosmic ray experimental results which possibly indicate new physics appearance at LHC energies. The consideration of interaction kinematics in colliders (interacting beams) and in cosmic rays (fixed target) leads to the following relation: the energy interval 1–14 TeV in LHC pp-interactions corresponds to the energy interval 10^{15}–10^{17} eV (1–100 PeV) in cosmic rays. But it is necessary to remark that pp-interactions cannot be studied in cosmic ray experiments, since primary cosmic rays (PCR) which consist of protons and nuclei interact with nuclei of nitrogen and oxygen.

Muons play a key role in many experiments as in cosmic rays so at accelerators upon two reasons. Firstly, muons can be produced only in processes of weak interaction (decays of more massive particles or interactions of muon neutrinos) and electromagnetic interaction (electroproduction of muon pairs). Secondly, muons are very simply detected and identified due to their very high penetrating ability and the possibility to detect them at large distances from the point of generation. Many discoveries in accelerator experiments were done using these unique peculiarities of muons. In cosmic rays, investigations of muon component are mainly directed at primary cosmic ray composition study, since the appearance of heavy nuclei in primary cosmic ray flux leads to increasing muon number. Of course, at that it is supposed that the interaction model is not changed with the increase of energy.

2. Results of cosmic ray muon experiments

Muon experiments in cosmic rays can be divided in two groups: investigations of multi-muon events (their multiplicity, local density, dependence on zenith angle) and measurements of single muon energy spectrum at various zenith angles.

During many years of cosmic ray muon component investigations, some deviations from expected results were periodically observed. But at continuation of experiments these deviations, as a rule, disappeared. However, the development of experimental techniques and construction of new detectors gave the possibility to obtain during last years a large set of experimental data which cannot be described by existing models.

In experiments performed in CERN at accelerator detectors ALEPH and DELPHI the excess of cosmic ray muon bundles with multiplicity about 100 particles which exceeded their expected amount even at assumption of pure iron composition of PCR was observed (Fig. 1, [1,2]).

But in these experiments no information about the energy dependence of this excess was obtained. The answer for this question was obtained in NEVOD-DECOR experiment, in which muon bundles are investigated in inclined EAS. At that, various zenith angles correspond to different intervals of primary particle energies. Measured dependences of local muon density spectra on zenith angles (Fig. 2, [3]) showed that in the interval 10^{15}–10^{16} eV a good agreement with expected results obtained with the assumption of a normal mass composition is observed (Fig. 2a). At increasing zenith angle, experimental data are shifted to a more heavy mass composition (Fig. 2b), up to pure iron nuclei (Fig. 2c).

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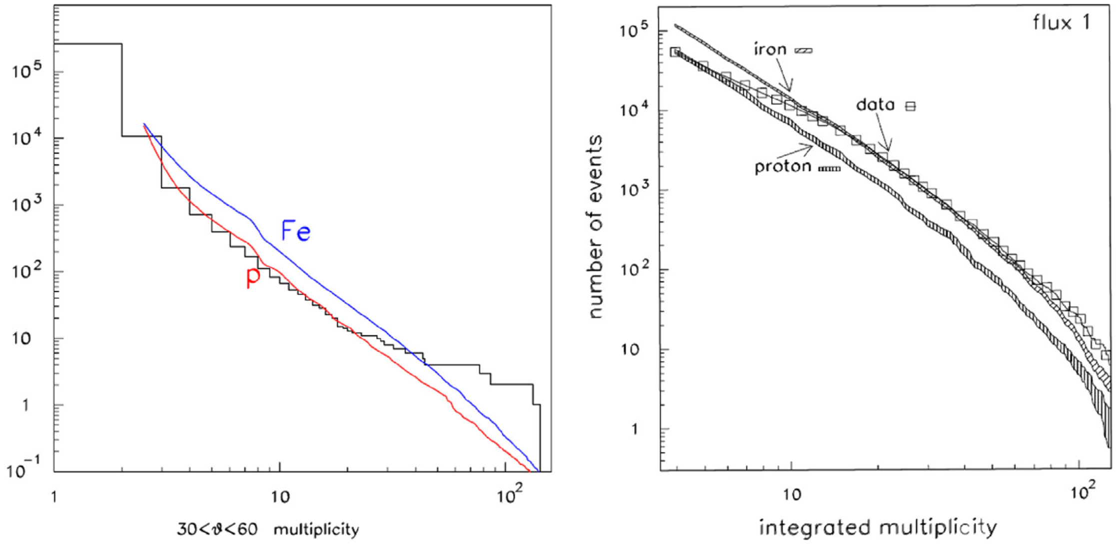

Fig. 1. Measured and simulated distributions of muon bundles detected in the ALEPH (left) and in the DELPHI (right) experiments.

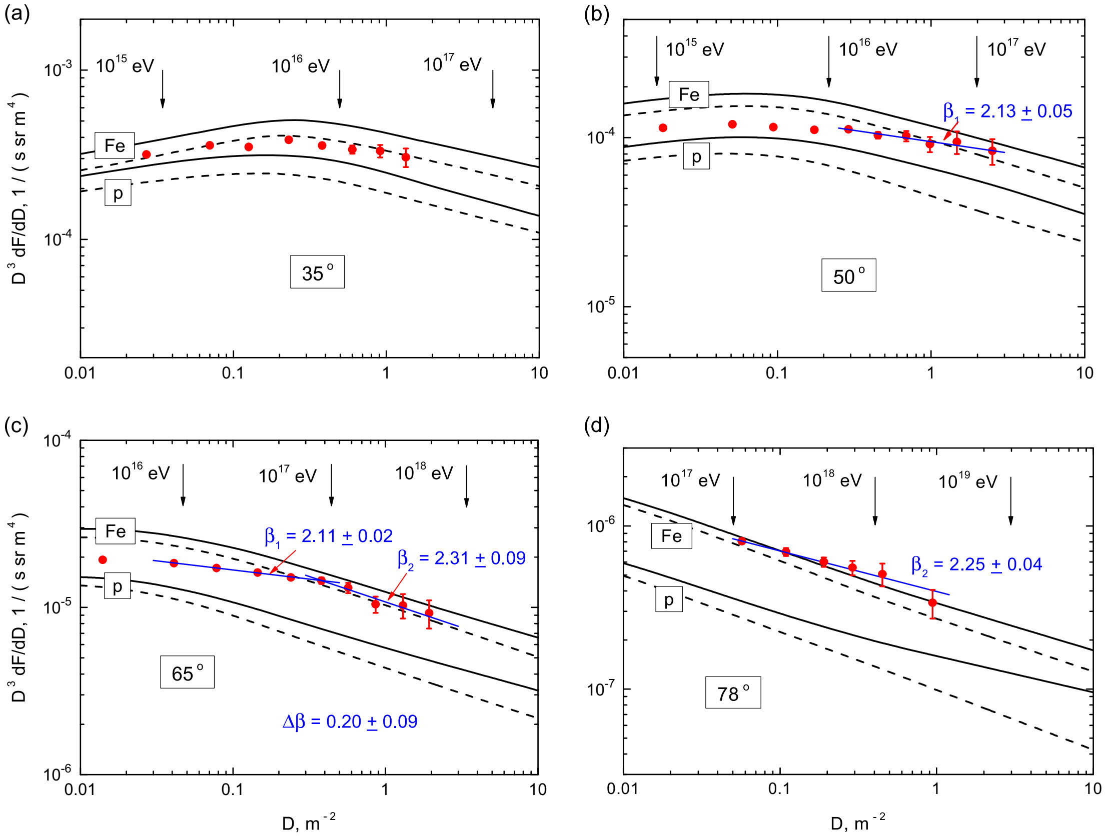

Fig. 2. Measured (points) and calculated differential local muon density spectra for 4 zenith angles (labels in the frames).

At a further increase of zenith angle, data lie higher than predicted results for pure iron composition (Fig. 2d). This result was confirmed in the biggest experiment on EAS investigations – Auger Observatory (Fig. 3, [4]). The excess of muons twice exceeds the expected values and is higher than calculations even for pure iron composition of PCR.

Measurements of muon energy spectrum often gave some excess of muons with energies of tens TeV. But deviations from predicted spectrum were not serious and were usually explained as fluctuations of the energy spectrum with a large slope.

The first result of evaluation of muon energy spectrum in the region of higher than 100 TeV was obtained in the analysis of Baksan Underground Scintillation Telescope (BUST) data using the method of multiple interactions of muons (method of e^+e^- pair meter). Though statistics in this energy region is not high (Fig. 4, [5]), nonetheless all detected events are reliably identified and well separated.

The second result was obtained at the biggest in the world under-ice detector IceCube with one cubic kilometer volume. Results are presented in Fig. 5 [6]. Muon energy spectrum was