Muon problem in UHECR investigations

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Abstract. In many UHECR experiments, some excess of muons is observed, which cannot be explained in frame of the existing theoretical models of hadron interaction. Attempts of its explanation through a heavy mass composition of PCR contradict the results of $X_{\text{max}}$ measurements. Really, the excess of muons appears already at lower energies ($10^{16} - 10^{17}$ eV), but in this domain it may be explained by the trend to a heavier mass composition, which is in a qualitative agreement with the galactic model of CR origin. The absence of heavy nuclei at energies of the order of $10^{18}$ eV requires to consider other possibilities of the appearance of muon excess, including changes of hadron interaction model. The actuality of the considered problem is connected with plans of future experiments in UHECR physics, in which the necessity of its solution must be taken into account.

1. Introduction
Muon is a very famous particle in modern physics. Beginning from its discovery, practically all muon investigations were connected with various puzzles and problems. Muon was the first particle of the second generation of quarks and leptons, but at that time nobody knew about this. And many investigators unsuccessfully tried to understand: what is the muon and what is the difference between muon and electron, except their masses? Then muon became the instrument for investigations of different tasks, especially in cosmic rays. The following characteristics are usually measured: energy spectrum, angular distribution and charge ratio – in single muon investigations; multiplicity, its zenith angle dependence and lateral distribution – in muon bundle investigations, which often are combined with EAS detection. In this paper, a brief history of such investigations is presented and modern situation with cosmic ray muon observations is discussed.

2. Brief history of CR muon investigations
Since most part of muons are generated in decays of $\pi$- and $K$-mesons, some correspondence between intervals of muon energies and primary cosmic ray (PCR) energies exists. Of course, this correspondence depends on PCR composition but in the first approximation this dependence can be ignored.

2.1. PCR energies below $10^{15}$ eV
This interval corresponds to muon energies less than about 100 TeV. Investigations of these muons were continued for several decades, various intriguing results were obtained and some puzzles were solved. The first of them was a discrepancy between the results of muon energy spectrum measurements by magnetic spectrometer and underground muon flux intensity data, which was converted into energy spectrum. This problem was solved by taking into account various methodical
circumstances which led to overestimation of measured muon energies in magnetic spectrometers, on the one side, and re-consideration of muon energy loss due to bremsstrahlung and pair production processes, their fluctuations and more correct evaluation of rock composition in the places of measurements, on the other.

Then very intriguing data of Keuffel’s group about zenith angle distribution appeared, which evidenced for an existence of so-called prompt process (more quick compared with $\pi^-$ and $K^-$-decays) of muon production. And though these results appeared finally wrong, they stimulated the searches of charmed particle production in accelerator experiments. In cosmic rays, contribution of charmed particles to muon energy spectrum was investigated in MSU, MACRO, LVD experiments. Obtained estimates of the value $R$, which gives the ratio of the number of prompt muons to the number of pions, had some straggling but, on average, were in an agreement with predicted values extrapolated from the accelerator data.

A critical review of results of muon energy spectrum investigations below 10 TeV was done in paper [1]. Review of results up to about 100 TeV can be found in [2]. The main conclusion from these results is the following: there are no serious evidences of the necessity of introduction of any new process for explanation of results of CR muon investigations at energies below 100 TeV, which correspond to PCR energies below $10^{15}$ eV.

### 2.2. PCR energy interval $10^{15} – 10^{17}$ eV

This energy interval was investigated in numerous EAS experiments: MSU, KASCADE, EAS-TOP, etc. Since usually there are no technical possibilities of muon energy measurements in EAS experiments, only multiplicity of muons was evaluated and compared with the number of electrons (more correctly, with the total number of charged particles). The increasing excess of $N_\mu / N_e$ – ratio with the growth of $N_e$ in comparison with the expectation was observed in different experiments. And though, in principle, two possibilities of explanation of this effect exist: a change of PCR composition and a change of interaction model, in most part of papers the first variant was considered. The main argument in favor of this choice is a good agreement with a galactic model of PCR origin, which predicts the change of the composition to heavy nuclei (up to iron) with the increase of energy.

The results of muon energy spectrum measurements above 100 TeV (BUST [3] and IceCube [4]) appeared only recently (Figures 1 and 2). The observed excess of muons with such energies in

![Figure 1](image1.png) **Figure 1.** Differential muon energy spectra for vertical direction measured in various experiments [2]. The curves correspond to different spectrum models. BUST results obtained by means of multiple interaction method [3] are added (solid diamonds).

![Figure 2](image2.png) **Figure 2.** Results of muon energy spectrum investigation in Ice Cube for different zenith angles [4]. Excess of VHE muons at moderate zenith angles in comparison with CORSIKA-based simulation is seen.
comparison with traditional muon energy spectrum can testify to inclusion of new physical process of muon generation.

2.3. **PCR energies above** $10^{17}$ **eV**

The main peculiarity of this energy region, as many physicists believe, is the transition from galactic cosmic rays to extragalactic ones. In this case, the composition must be changed in favor of more light nuclei (may be, pure protons) and results of measurements of $X_{\text{max}}$ suggest this. But measurements of muons testify in favor of a heavy composition, and in some experiments (e.g. [5]) give some excess of muons even compared with pure iron composition of cosmic rays (Figure 3). This result was confirmed in Auger experiment [6] (Figure 4). This problem was discussed in many talks at UHECR Workshop 2012 in Geneva. Apparently, in the frame of existing models of cosmic ray origin and their interaction it is impossible to find a solution of this muon puzzle, and introduction of a new model of interaction is required (see e.g. [7]).

![Figure 3](image3.png)

**Figure 3.** Differential spectrum of PCRs (with respect to energy per particle). Open symbols: experimental data from AGASA, HiRes, Pierre Auger Observatory, Telescope Array. Solid symbols are spectrum estimates reconstructed on the basis of DECOR data on muon bundles under two assumptions about mass composition for five different models of hadron interaction.

![Figure 4](image4.png)

**Figure 4.** Results of muon number measurements in the Auger experiment for inclined EAS [6].

### 3. How to solve the muon puzzle

In general, there are two main results above $10^{15}$ eV, which are usually used for PCR composition evaluation: increasing excess of $N_\mu / N_e$ ratio in comparison with simulations from the knee energy up to GZK cutoff, and changes in $X_{\text{max}}$ behavior: firstly relatively sharp shift of $X_{\text{max}}$ to iron composition and then a more slow return to light composition. Such behavior can be explained, e.g., in the frame of a model suggested in [8], in which it is supposed that PCR energy spectrum and composition in the interval between the knee and GZK-cutoff are not changed seriously and practically all (at least the main) changes in observed characteristics of EAS and muon flux are connected with changes of interaction model. In particular, a possibility of generation of quark-gluon plasma (QGP) blobs above the knee energy with a very large global orbital momentum was considered in [8].

In this case, firstly QGP blobs will be produced in interactions of heavy nuclei and only then in interactions of light nuclei. Since decays of QGP blobs with a large global orbital momentum into...
light quarks will be suppressed, decays into top-quarks will give considerable missing energy carried away by very high energy neutrinos, and seriously change the EAS development due to increasing secondary particle multiplicity and possible suppression of neutral meson production. As a result, the observed EAS energy spectrum will be different from PCR energy spectrum. Correspondingly, the measured composition will be another than in PCR.

How is it possible to check this new approach? There is the only parameter, measurements of which can give the answer for this question. This is muon energy. At production of heavy particles (e.g., top-quarks) very high energy (> 100 TeV) muons must appear. Therefore, measurements of the inclusive muon energy spectrum are the best way to check this hypothesis, and preliminary results [3,4] confirm it.

At higher primary energies, when the total number of top-quarks will be increased, it is possible to measure energy deposit of EAS muon component. A more rapid increase of muon energy loss in comparison with predictions from the normal EAS development will testify about new processes of VHE muon generation.

Of course, corresponding experiments can be performed at LHC. But taking into account that for energies < 14 TeV in the center-of-mass system QGP blobs can appear only in nuclei-nuclei interactions, such searches may require the development of new methods of top-quark observation.

4. Conclusion
Results of muon investigations in various experiments with a high probability confirm the change of the hadron interaction model at ultra-high energies, and production of QGP blobs may be considered as a good version of such model.

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