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INFLUENCE OF THE RESULTS OF UHECR DETECTION ON THE LHC EXPERIMENTS

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Abstract. The cosmic ray energy region $10^{15} \div 10^{17}$ eV corresponds to LHC energies $1 \div 14$ TeV in the center-of-mass system. The results obtained in cosmic rays (CR) in this energy interval can therefore be used for developing new approaches to the analysis of experimental data, for interpreting the results, and for planning new experiments. The main problem in cosmic ray investigations is the remarkable excess of muons, which increases with energy and cannot be explained by means of contemporary theoretical models. Some possible new explanations of this effect and other unusual phenomena observed in CR, and ways of searching for them in the LHC experiments are discussed.

Keywords: cosmic ray energy spectrum, cosmic ray composition, EAS, muons, quark-gluon matter.

1. Introduction

The discovery of the Higgs boson is the main task for LHC, and this task will be solved in the nearest future (positively or negatively[1]). However, this gigantic experimental complex will continue to work, and its possibilities will continue to expand. The question: "What are the next tasks?" is therefore very topical. Of course, there are many tasks connected with investigations of hadron-hadron interactions at LHC energies, tests of existing theoretical models behavior at such energies, etc. There are also many new theoretical ideas: supersymmetry, dark matter, etc., which will be searched at LHC energies.

In parallel with the development of accelerator equipment and experiments, corresponding investigations have been conducted in cosmic rays. LHC energies of $1 \div 14$ TeV correspond to the interval $10^{15} \div 10^{17}$ eV in the laboratory system for pp-interaction (for nuclei–nuclei interactions the upper limit can be higher). And namely at these energies many interesting and sometimes unusual results have been observed in CR investigations.

Of course, investigations in cosmic rays have many drawbacks compared to accelerator experiments, since in cosmic ray interactions many parameters of particles are unknown: the type of particle, its energy, arrival direction, etc. In addition, the results of CR experiments can be interpreted in two ways: as an investigation of particle interaction if to believe that the energy spectrum and composition of CR are known, and as a study of the characteristics of CR flux if to assume that hadron interaction model is known. One of the main disadvantages is the poor statistics, since CR flux decreases very rapidly with the increase in energy. However, numerous CR experiments have shown that below 10^{15} eV no serious deviations of the results of the measurements from the standard CR energy spectrum and composition and interaction model have been observed. The purpose of this paper is to analize the consequences for the LHC experiments that follow from the results of CR investigations at energies more than 10^{15} eV.

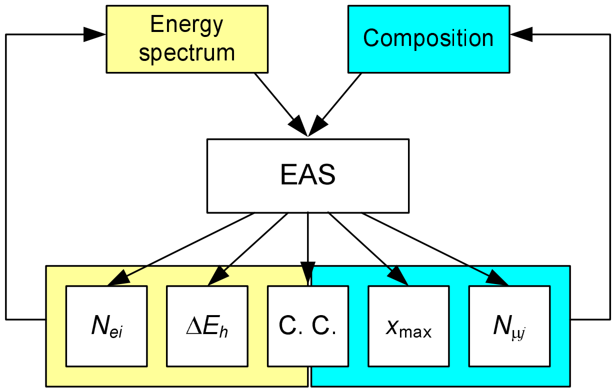

Figure 1. General scheme of EAS investigations.

2. Evidence of new physics in the CR experiments

Investigations of cosmic rays with energies more than 10^{15} eV can be conducted at the Earth surface only, since the flux of such particles is very small and very large detectors are required. Primary CRs interact with air nuclei at high altitudes, and the results of these interactions are detected. The general scheme of a CR study with energies more than 10^{15} eV is illustrated by Fig. 1.

In principle, it is possible to detect all secondary components: number of electrons N_e (more exactly, all charged particles), number of muons N_μ, energy deposit of EAS core ΔE_h, longitudinal shape of EAS development by using Cherenkov or fluorescence radiation (C.C., cascade curve), maximum of EAS de-

[1] During the preparation of this paper, the discovery of the Higgs boson was announced.

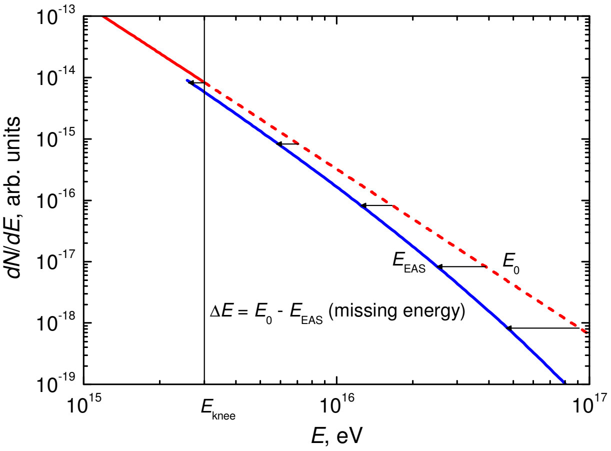

FIGURE 2. The change in the CR energy spectrum at the appearance of the missing energy.

velopment $X_{\max}$. In recent time, new parameters of EAS have been also investigated: D_{μ} – local muon density and N_{n} – number of EAS neutrons.

In principle, two approaches to the analysis of measured EAS parameters are possible:

– A cosmophysical approach, in which it is assumed that the EAS energy is equal to the energy of the primary particle, and all changes of EAS parameters in dependence on energy are the result of the energy spectrum or/and the composition of the CR changes only.

– A nuclear-physical approach, in which it is believed that changes of EAS parameters are the result of the inclusion of a new process of interaction or the production of new particles, states of matter, etc. In this case, the EAS energy is not necessarily equal to the primary particle energy.

The formation of the knee can be considered as the first evidence in favor of a change in the interaction model. As was first shown in [1], the knee in CR energy spectrum can be the result of the appearance of missing energy (Fig. 2), which is taken away by undetectable particles (three types of neutrinos) and muons, the energy of which is not usually measured. To implement this approach, a change in the interaction model at center-of-mass system energy about 3 TeV is required (for details, see [1]).

The second piece of evidence in favor of a change in the interaction model was obtained from the mountain experiments, mainly "Pamir" and "Chakaltaya", in which various unusual phenomena – halos, alignment, penetrating cascades, Centauros, Anti-Centauros – were observed. Though it was very difficult to evaluate the energy of the primary CR particles in these experiments, a comparison of the intensity of the observed events with the intensity of the cosmic rays shows that these events appear at energies between 10^{15} and 10^{16} eV. A more detailed description and an anlysis of the unusual events were made earlier [2].

The third piece of evidence in favor of new physics was obtained in CR investigations in muon experiments. First, it is the ever-increasing excess of the ratio of the number of muons to the number of electrons compared with the predicted ratio at energies $10^{15} \div 10^{17}$ eV. This increase can be explained by the change in the CR composition. However, a further increase in this ratio and the appearance of the muon excess even for the assumption of a pure iron composition can evidence at inclusion of new physical processes. The situation is the same with muons of very high energies (> 100 TeV). The tendency toward the appearance of a muon excess with increasing muon energy to 100 TeV is remarkable [3].

3. POSSIBLE VERSION OF A NEW INTERACTION MODEL

A possible model for describing all unusual phenomena observed in CR investigations above 10^{15} eV must satisfy the following requirements:

(1.) Threshold behavior (unusual events appear at several PeV only).

(2.) Large cross section (to change the EAS spectrum slope).

(3.) Large yield of leptons (excess of VHE muons, missing energy and penetrating cascades).

(4.) Large orbital momentum (alignment).

(5.) Quicker development of EAS (to increase the N_{μ}/N_{e} ratio and decrease the $X_{\max}$ elongation rate).

There are various ways to construct the necessary model, from including a new (e.g., super-strong) interaction at distances of about 10^{-17} cm and generating new massive particles ($m \sim 1$ TeV), to producing blobs of quark-gluon matter (QGM). We consider the last model, since it provides a demonstrable explanation of the inclusion of a new interaction and provides the predictions that can be checked both in CR investigations and in LHC experiments.

The production of QGM provides two main conditions:

– threshold behavior, since a high temperature (energy) is required for it;

– a large cross section, since the transition occurs from a quark–quark interaction to some collective interaction of many quarks:

$$\sigma = \pi \lambda^2 \to \sigma \sim \pi(\lambda + R)^2 \quad \text{or} \quad \pi(R_1 + R_2)^2, \quad (1)$$

where R, R_1 and R_2 are sizes of quark-gluon blobs.

However, a large value of the orbital angular momentum is required for an explanation of other observed phenomena.

As has been shown by Zuo-Tang Liang and Xin-Nian Wang [4], a globally polarized QGP with large orbital angular momentum which increases with energy as $L \sim \sqrt{s}$ appears in non-central ion–ion collisions. In

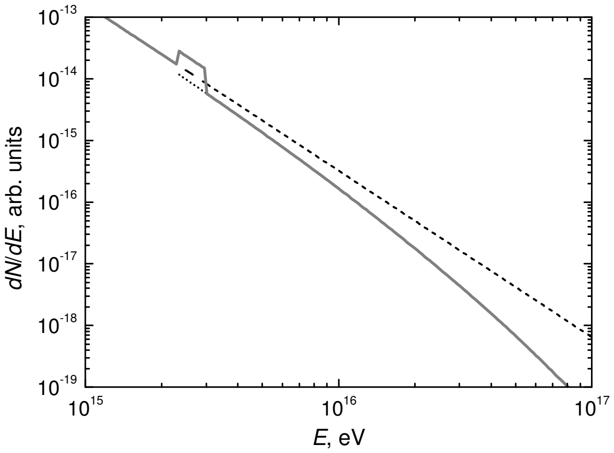

FIGURE 3. The production of the knee with some "bump" in the nuclear-physical approach.

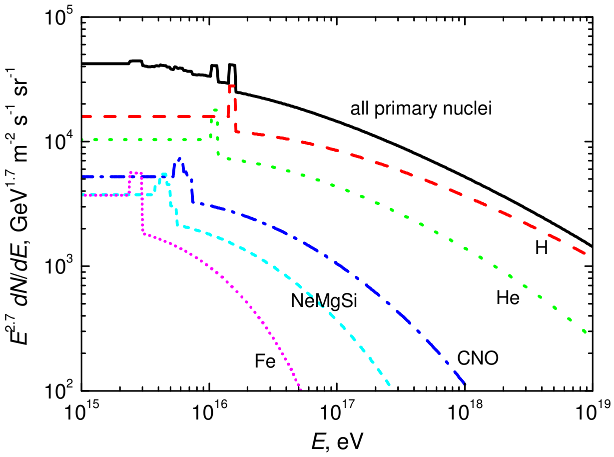

FIGURE 4. Energy spectra of basic groups of CR nuclei and the formation of the all-particle spectrum.

this case, a blob of quark-gluon matter can be considered as a usual resonance with a large centrifugal barrier. Centrifugal barrier $V(L) = L^2/2mr^2$ will be large for light quarks but small for top-quarks or other heavy particles. The orbital angular momentum value can be of the order of 10^5 [5]. The probability of the production of top–antitop pairs therefore increases.

However, simultaneous interaction of many quarks changes the energy in the center-of-mass system drastically:

$$\sqrt{s} = \sqrt{2m_p E_0} \to \sqrt{2m_c E_0}, \qquad (2)$$

where the mass of the QGM blob $m_c \approx nm_N$. At threshold energy, $n \sim 4$ (α-particle). The $t\bar{t}$-quarks that are produced take away the energy $\varepsilon_t > 2m_t \approx 350$ GeV, and taking into account the fly-out energy, $\varepsilon_t > 4m_t \approx 700$ GeV in the center-of-mass system.

Top-quarks decay in the following way: $t\bar{t} \to W^+(W^-) + b(\bar{b})$. In their turn, W-bosons decay into leptons ($\sim 30\,\%$) and hadrons ($\sim 70\,\%$); $b \to c \to s \to u$ with the production of muons and neutrinos.

4. Consequences for CR experiments

One part of the t-quark energy gives the missing energy (ν_e, ν_μ, ν_τ, μ), and another part changes the EAS development, especially its beginning, the parameters of which are not measured. As a result, additional muons appear, the measured EAS energy E_{EAS} will not be equal to the primary particle energy E_0, and the measured spectrum will be different from the primary spectrum (Fig. 2). Transition of particles from energy E_0 to energy E_{EAS} leads to a bump in the energy spectrum near the threshold (Fig. 3), which appears if we sum the two solid curves in Fig. 2. The appearance of other bumps in Fig. 4 is explained in the same way.

Since not only high temperature (energy) but also high density is required for QGM production, the threshold energy for the production of a new state of matter for heavy nuclei will be less than for light nuclei and protons. The heavy nuclei (e.g., iron) spectra are therefore changed **earlier** than the light nuclei and proton spectra.

The measured spectra of different nuclei **will not** correspond to the primary composition (Fig. 4). Thus, the observed increase in the mass of the CR composition is explained not by its real change, but by increasing detection probability of EAS generated by heavy nuclei.

In framework of this hypothesis, the so-called muon problem (muon puzzle) – the excessive number of measured EAS muons compared to the simulated number even for pure iron composition of primary CR – can be solved, since with 70 % probability W-bosons decay into hadrons (mainly pions) with an average number of about 20, and the multiplicity of secondary particles (and also muons) begins to increase more sharply than the existing models predict.

There is a more interesting situation with the muon energy spectrum. As was shown in the first paper about the nuclear-physical approach to the explanation of the knee [1], in this case a considerable excess of very high energy muons (> 100 TeV) must appear. Figure 5 presents the results of muon energy spectrum simulation in the framework of the QGM model. Since CORSIKA does not include $t\bar{t}$-quark production, the well-known PYTHIA code was used to introduce them. One can see that a remarkable excess of muons appears only at energies near 100 TeV. The contribution of $t\bar{t}$-quarks leads to a sharper increase of the muon spectrum than in the case of so-called prompt muons.

It is a very difficult task to get experimental data at such energies, and the corresponding results have been obtained only in recent years [6, 7].

Since there are no other ways to generate VHE muons, apart from the production of massive particles (state of matter), these results practically prove the approach considered here. If this effect does not disappear when there is a further increase in the statistics in the IceCube experiment, it will provide excellent proof of the validity of the nuclear-physical approach.

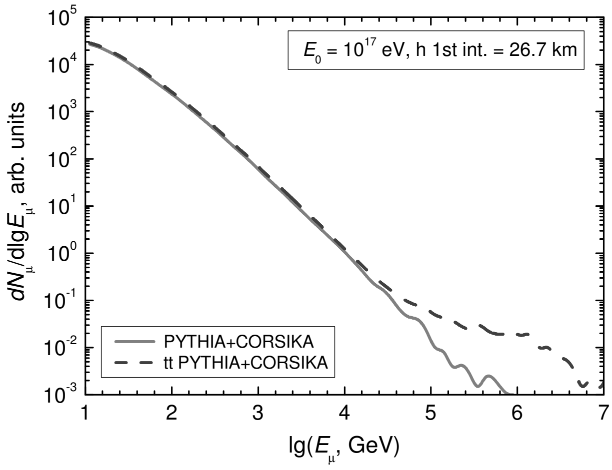

Figure 5. The differential muon energy spectrum simulated by CORSIKA with the $t\bar{t}$-quarks included from PYTHIA.

Another way is to have measurements of the EAS muon energy deposit below and above the knee. A change in the behavior of this value at the transition through the knee energy will also provide serious proof of the nuclear-physical approach.

5. Consequences for the LHC experiments

On the face of it, the search for QGM with the characteristics described above (excess of t-quarks, excess of VHE muons, sharp increasing of missing energy, etc.) is a very simple task. However, there is apparently no possibility to observe it in pp-interactions even at full LHC energy 14 TeV, since larger energies are required for that.

In fact, detailed investigations of pp-interactions at total energy 7 TeV showed very good agreement with the predictions of existing theoretical models, and no evidence of new physics was obtained [8]. However, in nuclei–nuclei interactions some deviations were observed. The first of them is sharper increase in the charged particle multiplicity than in the predictions of the simulations (Fig. 6 [9]) in the interactions of the nuclei. Of course, a single experimental point is not sufficient to draw serious conclusion about new physics, but the tendency is very clear.

The second result which can provide evidence in favor of QGM production is the detection of highly asymmetric dijet events (Fig. 7, [10]). In the framework of the model considered here, these events can be explained very simply. When a top-quark decays in the center-of-mass system, the kinetic energy is distributed as $T_b \sim 65$ GeV, and $T_W \sim 25$ GeV. If one takes into account the fly-out energy of the top-quark, T_b can be more than 100 GeV. In the case that the b-quark gives a jet and W decays into $\sim 20\,\pi$, the ATLAS event can be obtained.

Some evidence of QGM production in the nuclei–nuclei interactions in the LHC experiments are therefore obtained. However, a more detailed investigation of the new state of matter at LHC will be not so easy, since usual accelerator methods of searching for relatively narrow resonances in pp-interactions cannot be applied in the case of blobs of QGM production. When hot blobs of QGM decay, it is very difficult to wait for the reconstruction of a narrow resonance state. Apparently, new methods for investigations of the new state of matter will need to be developed. One possible method is an evaluation of the missing energy, an increase in which with total energy will provide evidence in favor of the production of QGM or some other new state of matter.

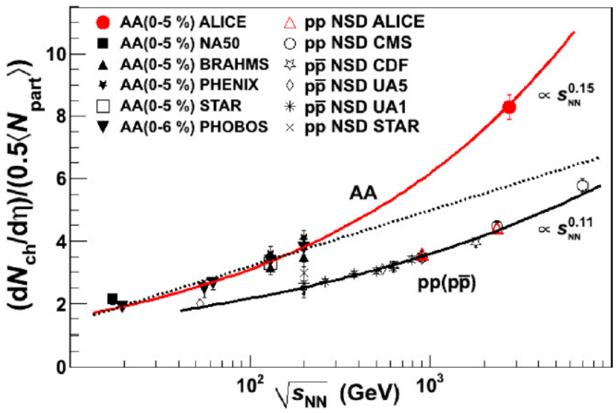

Figure 6. Results of charged particle multiplicity measurements at LHC energy 3 TeV [9].

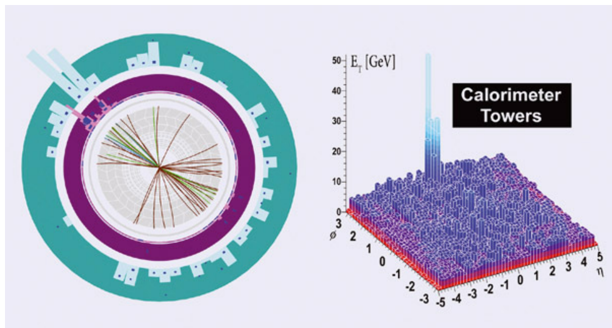

Figure 7. Highly asymmetric dijet event observed in ATLAS in heavy ion collisions [10].

6. Discussion

It should be noted that the considered model of QGM blob production can be checked in very different ways in CR investigations and in LHC experiments. Since the life time of a QGM blob is very short (in spite of its very large orbital angular momentum and centrifugal barrier), it is very difficult to obtain any evidence of its existence by measuring most of the usually detected parameters. Apparently, two values can be used: the multiplicity of charged particles, which will be sharply increased with increasing energy and mass of the interacting nuclei, and the average missing energy in certain types of events.

From this point of view, the experiments in cosmic rays have some advantages connected with the large longitudinal momentum of the primary particles. For this reason, the muons (and neutrinos) from the W-boson decays have energy not of $\sim 40\,\text{GeV}$ (as in the center-of-mass system) but of more than 100 TeV. Unfortunately, very large detectors are required for muons with such energy. It is therefore very difficult to predict in what kind of experiment an exhaustive proof of new physics (production of QGM blobs, or some other new state of matter) will be obtained, though the author has no doubt that the nuclear-physical approach is correct.

7. Conclusions

The approach considered here, based on the production of QGM blobs, which allows an explaination of practically all problems of cosmic ray investigations above 10^{15} eV, shows that this new physics at LHC energies can be found in nuclei–nuclei interactions only. Two clear predictions can be made: a quicker increase in charged particle multiplicity and in missing energy with the increase in energy and the mass of the interacting nuclei.

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Discussion

Todor Stanev — You gave the impression that we have no idea about particle physics. There is a paper by D'Enterria et al. that compares the LHC results at $\sqrt{s} = 7\,\text{TeV}$. Cosmic ray models predict measurements better than some versions of PYTHIA.

Anatoly Petrukhin — In the paper of D'Enterria et al., only pp-interactions are considered. The idea of my talk is the following. QGP will appear firstly in interactions of heavy nuclei (e.g., iron) with nuclei of the atmosphere. Apparently, the threshold of QGP production in pp-interactions will be at energies higher than 14 TeV. Of course it is possible that some deviations can begin at this energy, but at energy 7 TeV QGP blobs cannot be produced. How are we to search top-quarks in nuclei–nuclei interactions? I believe nobody has thought about this. Therefore we have time to obtain additional proof of QGP production in cosmic ray investigations.