IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Cosmic ray muon study with the NEVOD-DECOR experiment

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2017 J. Phys.: Conf. Ser. 866 012010

(http://iopscience.iop.org/1742-6596/866/1/012010)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 131.169.5.251
This content was downloaded on 11/07/2017 at 20:44

Please note that terms and conditions apply.

You may also be interested in:

Scintillator tiles read out with silicon photomultipliers
O. Pooth, T. Radermacher, S. Weingarten et al.

Electronic calibration of the ATLAS LAr calorimeter and commissioning with cosmic muon signals
Carolina Gabaldón and the Atlas LAr Collaboration

NEVOD-DECOR experiment: results and future
O Saavedra, M B Amelchakov, N S Barbashina et al.

First measurements of cosmic muons with magnetic field in CMS
P Biallass, T Hebbeker and K Hoepfner

First demonstration of imaging cosmic muons in a two-phase Liquid Argon TPC using an EMCCD camera and a THGEM
K. Mavrokoridis, J. Carroll, K.J. McCormick et al.

Measurements of the energy spectrum of cascade showers initiated by muons in the Cherenkov water calorimeter NEVOD
S S Khokhlov, A V Borshevsky, D V Chernov et al.

Ground detectors for the study of cosmic ray showers
H Salazar and L Villasenor

The EEE Project: a sparse array of telescopes for the measurement of cosmic ray muons
P. La Rocca, M. Abbrescia, C. Avanzini et al.

Proposal of NEVOD-EAS shower array
I A Shulzhenko, M B Amelchakov, N S Barbashina et al.

VI School on Cosmic Rays and Astrophysics IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **866** (2017) 012010 doi:10.1088/1742-6596/866/1/012010

Cosmic ray muon study with the NEVOD-DECOR experiment

Oscar Saavedra San Martin

Istituto Nazionale di Astrofisica, INAF, Italy

saavedra@to.infn.it

Abstract. The experiment NEVOV-DECOR, which is desinged to study the cosmic muons at very inclined directions, is running under the collaboration of the Moscow Engineering Physics Institute, Moscow, Russia, and the Instituto Nazionale di Astrofisica and the Dipartimento di Fisica, Università di Torino, Italy. The main purpose of this experiment is to study the characteristics of the high multiplicity muons in muon bundles and their angular distributions. The result has shown the observation of the second knee at 10^{17} eV in the primary cosmic ray spectrum. In addition, we found that the number of high energy muons in EAS is more than 30% of what is predicted by the Monte Carlo models. This effect was found also by other experiments like Auger, but at primary cosmic ray energies higher than 10^{18} eV. We will present and discuss the main results of these investigations.

1. Introduction

To resolve the problem of the origin, acceleration and propagation of high energy cosmic rays, we need to know their energy spectrum and mass composition. If the energy of the primary cosmic ray is higher than 10^{15} eV, the only way to know the characteristics of the cosmic ray particles is through the study of Extensive Air Showers (EAS) at ground level. They are produced when the primary cosmic ray interacts high in the atmosphere.

The EAS are studied by means of their components: the electromagnetic component (with photons, electrons and positrons), the hadronic component (with protons, neutrons, pions, etc.), the leptonic component (with muons and neutrinos), and other signals produced by charged particles like Cherenkov light in the atmosphere, luminescence light, radio waves etc.

To detect each component, many types of detectors are used, like scintillators, water Cherenkov detectors, etc. They are located in many laboratories distributed in several places, and altitudes above sea level, or in underground laboratories, according to the purpose of the experiment and which of the component is being studied. The arrival directions of cosmic rays are isotropic, however if we study their zenith angular distribution there appears an absortion effect on the observed EAS due to the thickness of the atmosphere, from observations of the charged secondary particles in the EAS, and even more due to the Earth magnetic field.

In the primary interaction many secondary particles are produced, in particular, π's. Such particles can decay into μ's. The μ's suffer a feeble interaction through the atmosphere, therefore, they can transport direct information from the first hadronic interactions and consequently information about the primary particle. It is very important to study the cosmic muons mainly at very large zenith angle since most of the other components are absorbed in the atmosphere and the only survival component is the muonic one. The main objective of the cooperation between MEPhI and Torino institutions was the construction of the large area coordinate-tracking detector DECOR around the Cherenkov water calorimeter NEVOD [1] for investigations of multiple particle cosmic ray events at large zenith angles. The description of basic results of multi-muon event analysis are presented in this document. In particular, two new methods are described. They are connected with the EAS muon component investigation: the local muon density, D_μ (which is realized in the NEVOD-DECOR experiment [2]) and the muon bundle energy deposit, E_μ.

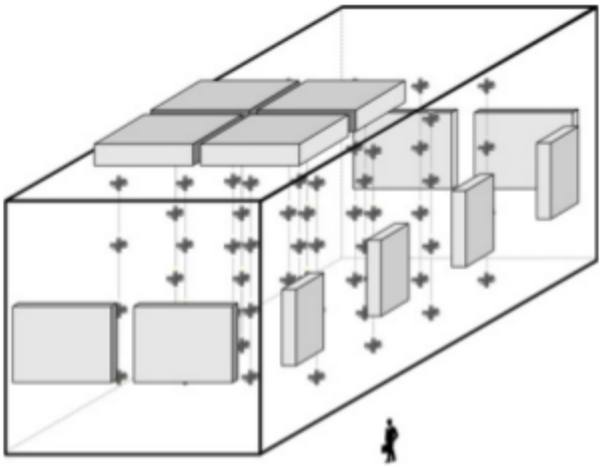

Figure 1. General layout of the NEVOD-DECOR experiment [2] (see the text for a description of the main components).

2. Experimental data

The general layout of the NEVOD-DECOR experimental complex is shown in fig 1. The NEVOD detector consists of a water Cherenkov tank with 2000 m^3 and is formed by a spatial lattice of quasi-spherical (QSM) optical modules each of them consisting of six photomultipliers with flat 15 cm diameter photocatodes. Thus the detecting latice has a nearly cubic shape, in total it includes 91 QSM. The side part of the coordinate-tracking detector DECOR is deployed in the galleries of the NEVOD building from three sides of the water tank. Two pairs of supermodules (SM) are located in the opposite short galleries and four supermodules in the long gallery. Each SM has an effective area of 8.4 m^2 and consists of eights planes of streamer tube chambers with resistive cathode coating hanged vertically with 6 cm spacing. The chambers are operated in a limited streamer mode with a continuous gas flow of an Ar+CO2+n-pentane mixture. The length of each chamber is 3.5 m. The planes of the chambers are equipped with a two-dimensional system of external read out strips (256 X- and 256Y-channels in each plane with 1.0 and 1.2 cm pitch, respectively). As a first level trigger condition for the SM, a 4-fold coincidence of signals from at least 2 odd and 2 even planes is used. The accuracy of the reconstruction of the tracks crossing the SM is about 1 cm in space and better than 0.7° and 0.8° for the projected zenith and azimuth angles, respectively.

In 2002-2007 a long series of measurements with the NEVOD-DECOR experiment were conducted. Net operation time with good quality data for the full configuration of the side DECOR was 19,922 h. The basic set of event selection conditions were based on the coincidences of the signals between different parts of the coordinate detector. The signals of the NEVOD QSM lattice and the CTS (a calibration telescope system that consists of two planes of scintillation detectors) were kept unchanged during the measurements. Selection of inclined muons bundles from DECOR data is based on the fact that tracks of muons originated in the atmosphere are nearly parallel. The data are analyzed part by part, for certain ranges of multiplicities and zenith angles. Phenomenological distributions of muon bundles as a function of particle multiplicity for several zenith angle intervals and in zenith angle for three values of the minimal number of muons are presented in figure 2. The obtained data on muons cover 6 orders of magnitude in the event intensity.

3. Local muon density spectra (LMDS): results and discussions

At zenith angles larger than 50-70^o, depending of the primary particle energy, EAS are detected at the ground level as, practically, muon component. Due to a large distance from the EAS generation point to the observation level, the transversal dimension of shower muons rapidly increases with the zenith angle, the effect being additionally enhanced by the particle deflection in the geomagnetic field. Therefore, a muon detector with sizes of tens of meters may be considered as a point-like probe. In an individual event, the local density of EAS muons at the observation point may be estimated as the ratio of the muon bundle multiplicity *m* to detector area for a given direction: $D_\mu \sim m/S_{\text{det}}$. [4,5].

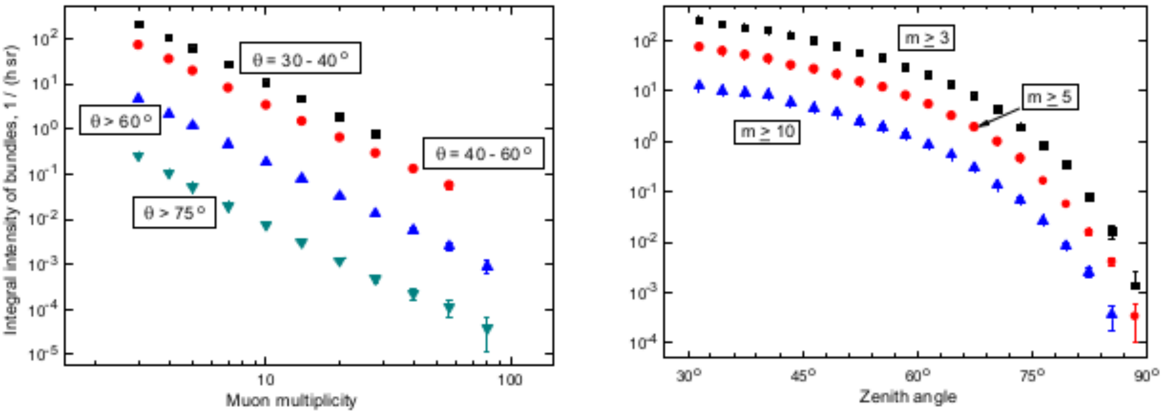

Figure2. Integral distribution of muon bundles as a function of particle multiplicity (*m*) for several ranges of zenith angle (left) and as a function of the zenith angle distribution of the bundles for different minimal number of muons.

Primary particles with different energies contribute to events with a certain muon density at distinct distances from the axis. However, due to the fast decrease of the primary cosmic ray (PCR) intensity, at increasing energies, the effective primary energy band appears relatively narrow (see figure 3, left).

It is important to note that at different zenith angles events with a fixed muon density are created by primary particles with substantially different energies that is, the event collection area is determined not by the detector size, but by the dimensions muon component in the EAS which near the horizon reach several kilometers. This fact allows to explore a very wide range of PCR energies by means of the LMDS method in a single experiment with a relative small detector. The dependence of the effective EAS collection area on zenith angle is shown in figure 3, right. At large zenith angle an important role is played by the Earth magnetic field (EMF) and the S_{eff} is sensitive to the field strength and direction. For zenith angles larger than 80 ^{o}, S_{eff} exceeds 1 km^2, which is sufficient to collect acceptable event statistics at energies near 10^{18} eV [4].

The distribution of the events in muon density-local muon density spectra- is sensitive to the shape of the spectrum of primary cosmic rays. Similarly to the spectrum of EAS in the number of muons, LMDS vary (mainly in absolute intensity) with the primary composition. Local muon density spectra are formed mainly by the central part of the EAS and are determined by the most energetic muons, and the most energetic parent hadrons, propagating near the shower axis, hence they carry additional information about the forward kinematical region of hadron interactions. A comprehensive description of the phenomenology of the LMDS technique and features of its application to the analysis of DECOR data on muon bundles was recently published in [3].

A general approach in the analysis of muon bundle data includes the following steps: reconstruction

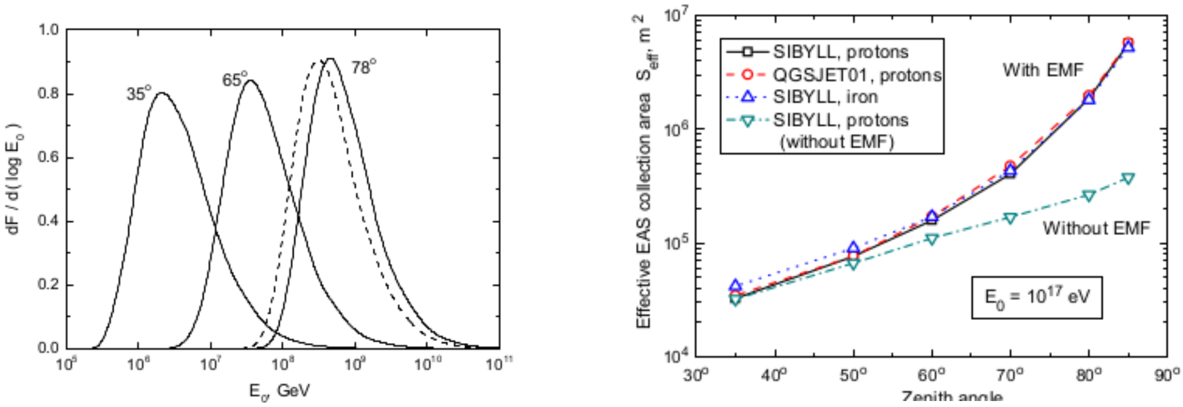

Figure 3 Left: Distribution of primary cosmic ray particle energies contributing to events with a fixed muon density (D_μ=0.2 muon/m^2) at different zenith angles. Solid curves correspond to calculations for primary protons, dashed curves, for iron nuclei. Right: Dependence of the effective EAS collection area on zenith angle in the LMDS technique.

of local muon density spectra in a detector-independent form from the measured distribution of muon bundle characteristics, taking into account Poisson fluctuations of the number of muons that hit the setup, triggering and selection conditions, detector efficiency, etc.; calculation of the expected LMDS for various assumptions about the primary spectrum, mass composition and hadron interaction models on the basis of 2-dimensional muon lateral distribution functions (LDF) simulated by means of the CORSIKA [5] code taking into account the geomagnetic field effects; and comparison of data with calculated results.

In figure 4, experimental LMDS reconstructed from DECOR data on muon bundles are compared with CORSIKA-based calculations for 4 different zenith angles (35°,50°, 65° and 78°). For comparison, a model of the primary flux with a power-law energy spectrum with differential slope +2.7 below the knee energy (4 PeV) and steepening to -3.1 above the knee was assumed. Absolute normalization was chosen according to the bulk of the experimental data around the knee presented in the review [6], two limiting cases of the mass composition (only protons and only iron nuclei) were considered. The curves in the figure correspond to two widely used hadron interaction models available in CORSIKA: SIBYLL 2.1 and QGSJET01 (dashed and solid curves, respectively). Arrows in the upper part of each frame indicate the values of effective (mean logarithmic) primary energies.

As it is seen from the results for moderate zenith angles (θ=35°, upper left frame) at energies around the knee the experimental LDMS is in a reasonable agreement with calculations, including the absolute normalization. The change of the LMDS slope is related with the knee in the primary spectrum. These results may be considered as an indirect check of the energy scale calibration.

At effective primary energies E_o> 10^{16} eV and zenith angles equal to 50° and 65° a progressive increase of the measured LMDS in comparison with calculations is observed, which can be interpreted as a trend to a heavier mass composition, though an alternative interpretation related with increasing deficit of muons in simulated EAS is also possible. Near primary energies equal to 10^{17} eV, a hint for a second knee was found [7], partial fits of the data obtained at zenith angle equal to 65° below and above this energy indicate the increase of the integral LMDS slope, β, by 0.20 ± 0.09. This result is also in quantitative agreement with slope estimates derived from the data at other zenith angles (thin lines in the figures, the intervals of $E_o = 10^{16}$ -10^{17} for 50° and $E_o > 10^{17}$ eV for 78°). By combining statistically independent data for different angles, we obtain $\Delta\beta = 0.15 \pm 0.04$. Taking into account the relation between the LMDS slope β and the integral primary energy spectrum index γ, i.e. $\beta \sim \gamma/0.9$ [4], it corresponds to an increase of the primary spectrum slope by $\Delta\gamma = 0.13 \pm 0.04$.

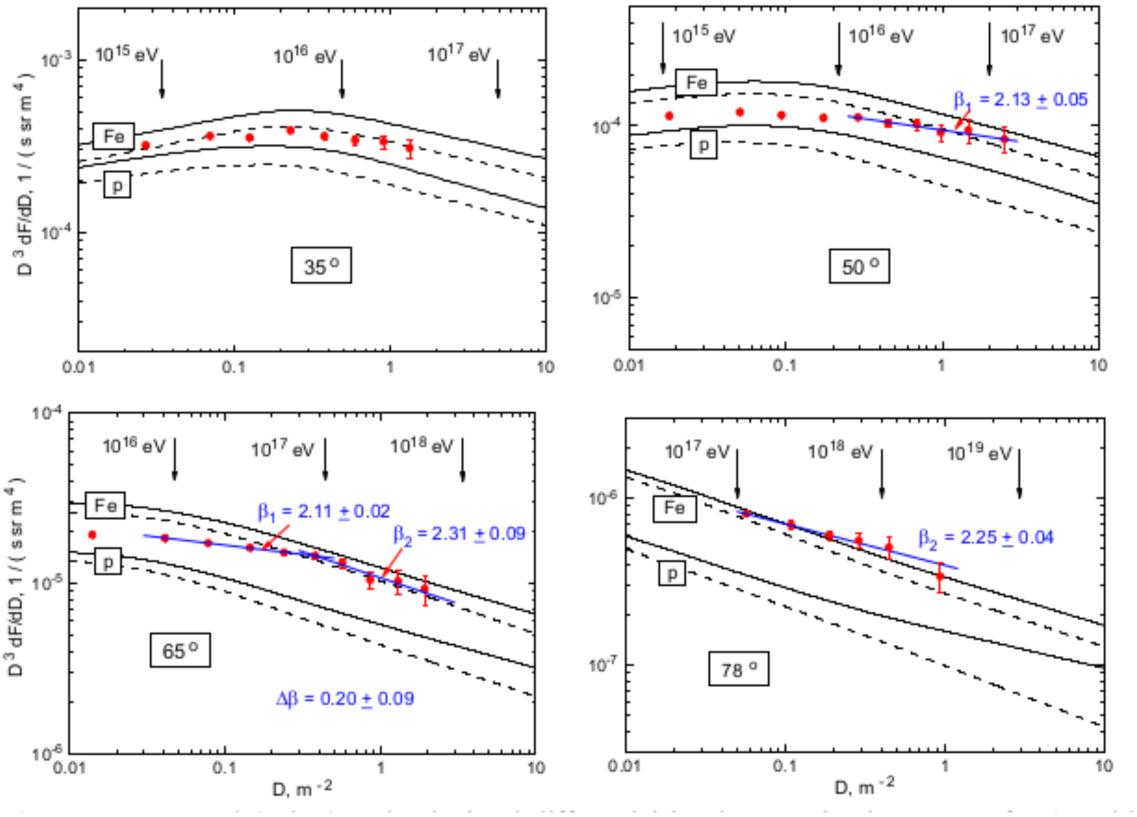

Figure 4. Measured (points) and calculated differential local muon density spectra for 4 zenith angles (labels are shown in the frames). Thin lines represent partial power-law fits of the data points between 10^{16} and 10^{17} eV (integral spectrum slope β_1) and above 10^{17} primary energy (integral spectrum slope β_2).

The conclusion about the steepening of the all-particle cosmic ray spectrum near 10^{17} eV was confirmed by KASCADE-Grande experiment [8].

Finally, data points at high muon densities and the largest zenith angle (78°), which correspond to primary energies around 10^{18} eV, lie near the upper edge of the calculation uncertainty band and even somewhat exceed the expectation for pure iron flux.

The relation between the local muon density spectrum and the primary cosmic ray flux is determined by the muon LDF, which in turn depends on the hadron interaction model and primary particle type. Therefore under certain assumptions about primary mass composition and hadron interaction model, the LMDS may be converted into an estimation of the primary cosmic ray spectrum [9]. Such procedure was applied to data samples with high muon multiplicities ($m \geq 10$) and two zenith angle intervals with: $\theta \geq 80^{\circ}$. These data correspond to the mean logarithmic primary energies around 10^{18} eV and higher. The conversion was performed with two assumptions on the primary composition (pure protons and pure iron nuclei) using five different hadron interaction models available in the recent CORSIKA versions: SYBILL 2.1, QGSJET01, QGSJET-II, EPOS1.61 and EPOS1.99. For every sample 10 estimates of the differential primary energy spectrum has been obtained.

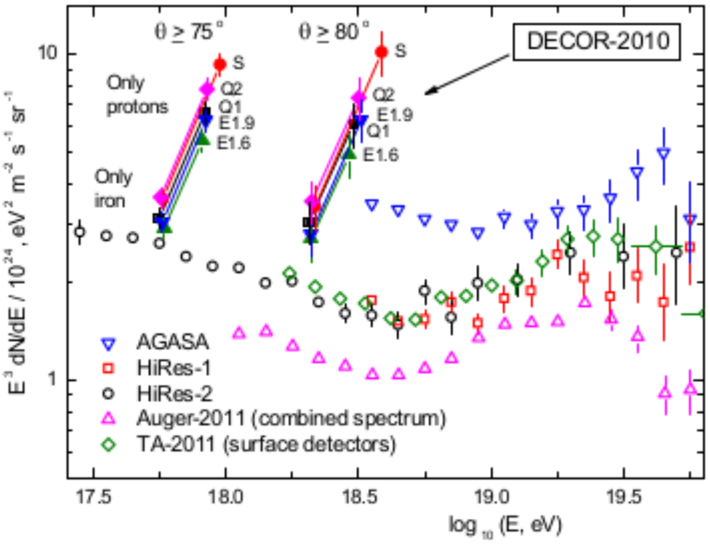

Figure 5. Comparison of differential primary spectrum estimates derived from DECOR data on muon bundles (dark points) with results of EAS measurements in AGASA [10], HiRes [11], Auger [12] and TA [13] experiments.

In figure 5, primary energy flux estimates derived from DECOR data are compared with results of recent measurements of PCR energy spectrum in the EeV energy range. Though a reasonable agreement in absolute normalization with AGASA data [10] is observed, it is seen from the figure that none of the examined interaction models allows us to match the data on muon bundles at large zenith angles with PCR spectrum measurements performed by means of the fluorescence method in HiRes [11], AUGER [12] and Telescope Array [13] experiments, even for the heavy (iron nuclei) mass composition.

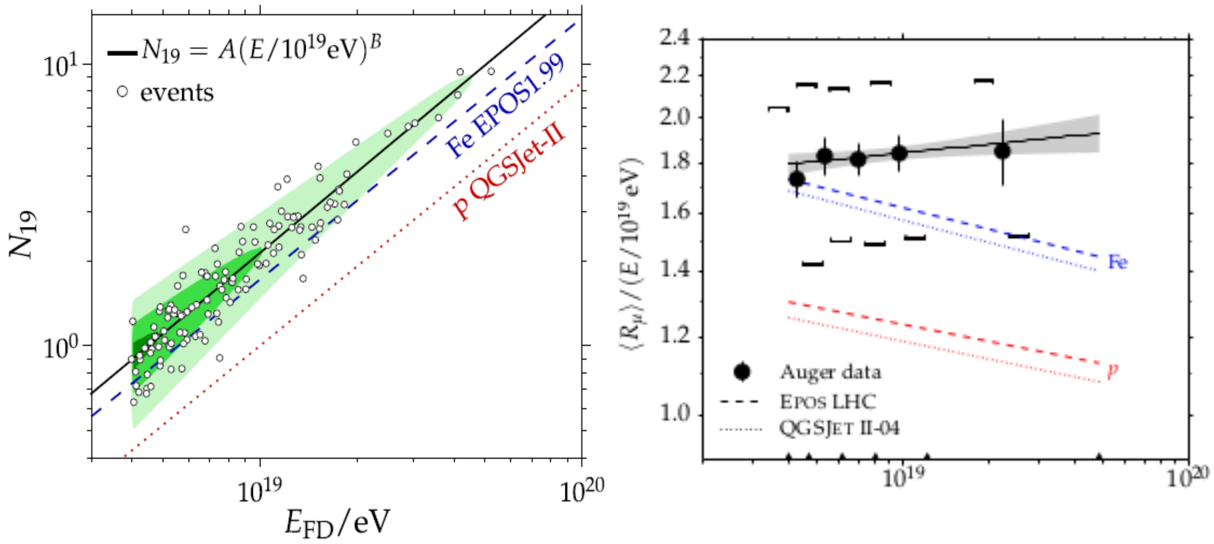

Figure 6. Excess of the number of muons in inclined EAS from The Pierre Auger Observatory data. a) Number of muons as measured by the fluorescence detectors, FD. [16] They concluded: *"We find that none of the current shower models, neither for proton nor for iron primaries, are able to predict as many muons as are observed b)* Average muon content $<R\mu>$ per shower energy *E* as a function of energy *E*. [17] they concluded *"We observe a muon deficit in simulations of (30-80)% at 10^{19} eV depending of the model".*

This contradiction becomes even more significant, if one takes into account that both HiRes and Auger data on $X_{\max}$ distribution favor a light (predominant proton) primary composition near 1 EeV [14,15]. If we assume proton primaries, the observed intensity of muon bundles will be about 2-3 times higher than the expectation. Recently, based on the analysis of the surface detector (SD) data on the muon content in inclined EAS simultaneously registered by means of the fluorescence detector (FD) the Auger collaboration came to the same conclusion that "none of the current shower models, neither for proton nor for iron primaries, are able to predict as many muons as are observed. [16,17]. This is shown clearly in figure 6.

The obtained results indicate with high probability the appearance of new processes of muon generation at very high energies that can explained by the appearance of new state of matter.

Acknowledgments
The author wishes to acknowledge prof. A. Petrukhin, spokesman of the experiment, and all his staff for his continuous encouragement to realize this experiment. I am also very grateful to Conacyt for the support trough the Mesoamerican Centre for Theoretically Physics.

References

[1] Aynutdinov, V. M. et al.; Astrophys. (1998) *Space Sci*. **258**, 105
[2] Amelchakov, M. B. et al.; (2001) *Proc 27th ICRC (Hamburg) vol 3 p 1267*
[3] Bogdanov, A. G. et. al.; (2010) *Phys Atom Nucl* **73** 1862
[4] Petrukhin, A. A. (for DECOR collaboration) *Nucl. Instru. Meth. Phys. Res* A **692** 228; and Saavedra O. (for DECOR collaboration) (2013) *Jour of Phys Conf Series* **409** 012009
[5] Heck, D. et. al.; (1998) *Forschunggszentrum Karlruhe Report* FZKA 6019
[6] Gaisser, T. K. and Stanev, T. *Particle Data Group* (2004) Phys Lett B **592** 228
[7] Yashin, I. I. et. al.; (2007) *Proc 30th ICRC (Merida Mexico)* vol 4 p 91
[8] Bertaina, M. et. al.; (2011) *Astrophys Space Scie Trans*. **7** 229
[9] Kokoulin, R. P. et. al.; (2009) *Nucl Phys* B *(Proc Suppl)* **196** 106
[10] Takeda, M. et. al.; (2003) *Astropart Phys* **19** 447
[11] Abbassi, R. U. et. al.; (2008) *Phys Rev Lett* **100** 101101
[12] Abraham, I. et. al.; (2010) *Phys Lett* B **685** 239
[13] Ikeda, D. et. al.; (2011) *Proc 32nd ICRC (Beijing, China)* vol 2 p 238
[14] Abbassi, R. et. al.; (2010) *Phys Rev Lett* **104** 161101
[15] Abraham, I. et. al.; (2010) *Phys Lett* **104** 091101
[16] Rodrigues, G. et. al.; (2013) *EPJ Web of Conf.* ***53*** *07003*
[17] A.Aab, et. al.; (2015) *Phys. Rev.* D ***91*** *032003*