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Can We Observe the Quark Gluon Plasma in Cosmic Ray Showers ?

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Abstract

The detection of high energy cosmic ray interactions at the medium depth underground is studied. Detected high energy muons carry information about the initial interaction. This might reveal the effects resulting from creation of quark gluon plasma at high energy interactions of iron nuclei contained in cosmic rays with the air.

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1. Introduction

Recent measurements by KASCADE [1] have shown the increased proportion of heavier nuclei in cosmic rays at energies around the knee region (5×10^{14} eV up to almost 10^{17} eV). Although the more precise determination of the chemical composition is not yet feasible, the presence of Fe^{56} is quite plausible. This rises an interesting possibility to observe iron nitrogen and iron oxygen nucleus-nucleus interactions at energies beyond possibilities of terrestrial accelerators. Though both N^{14} and O^{16} are light nuclei[1)], the number of participating nucleons in head on collisions with iron nuclei goes to several tens. Thus given the available energy per nucleon, the formation of quark-gluon plasma might be possible. The conditions at which such interactions take place are unique and give an opportunity to investigate characteristics of quark-gluon plasma (QGP) inaccessible at terrestrial experiments. The interactions of iron nuclei take place at altitudes higher than 20 km and the secondary charged pions have large chance to decay into muons due to the thin air at these altitudes. While the decay products of the neutral pions undergo interactions throughout the whole atmosphere depth, the muons in a sense decouple from further shower development and are subjected only to multiple scattering. Moreover the big Lorenz factor helps to collimate the secondary particles into a narrow cone. As a result of all such phenomena there is a possibility to observe differences in muon production in some extensive air showers from what one would expect on the basis of standard models of high energy interactions.

The fact that the hard component of muons in extensive air showers carries information on the pion production in the initial stage of the shower development is of great importance. Hence, QGP aside, it is interesting enough to study the sensitivity of energetic muons to the details of the primary interaction dynamics. In this regard the QGP effects observed in the muon component of air showers will indicate the extent of the above mentioned sensitivity. Of course it is necessary to determine in more quantitative way what does it mean the 'hard component' and how to observe it. One simple method is to place the muon detection area underground at such depth that the overburden will filter out the energetic muons in an amount sufficient to carry the information on the initial interaction.

The aim of this paper is to study such effects and to learn the conditions necessary to detect at least some of the features demonstrating the presence of QGP in cosmic ray interactions with atmosphere. To achieve this, first a very simple model of QGP formation is presented in section 2. It is used to simulate the QGP and the results are then compared with the outcome of programs currently used for simulations of extensive air showers. The simulated data analysis and comparisons are presented in section 3. The conclusions are discussed in the final section.

2. Quark Gluon Plasma Simulation

The standard package used for simulation of cosmic rays interactions with the atmosphere is the program CORSIKA [2] supplemented by several models of high energy interactions of elementary particles. The properties of these models have been extensively studied

[1)] In principle also interactions with Ar^{40} may happen but these are suppressed by factor more than 100 according to CORSIKA simulations.

$< p^{\pi} >$	$\mathcal{R}_h$ *ratio*		
MeV	0.1	0.2	0.4
60	1492 (880)	2743 (1717)	6764 (3802)
120	1389 (791)	2610 (1634)	6332 (3568)
300	1074 (680)	2165 (1398)	4918 (2614)
1000	674 (393)	1260 (825)	3093 (1808)

Table 1: The mean numbers of pions produced in QGP. The figures given in the brackets represent the R.M.S. values.

in [3], [4]. The best agreement with the experimental data of KASCADE is achieved by QGSJET [5] and VENUS [6]. QGSJET gives somewhat better results. VENUS predicts slightly bigger number of muons per event than QGSJET at energies in the range $10^{14}\ eV - 10^{16}\ eV$. As this might blur or hide the QGP originated muons the VENUS model has been adopted as the basis for comparisons in order to test the QGP effects in less favourable conditions. Further reasons for this choice were the nice documentation of VENUS and the fact that QGP simulations supplemented by VENUS simulations were possible without any intervention into VENUS code.

The key factor in QGP modelling is the number of nucleons participating in the first interaction with atmosphere N_{int}. In case that N_{int} is bigger than certain limit, N_{hot} nucleons are supposed to melt down into QGP. The fractions of melted nucleons used in simulations were 10 %, 20 % and 40 % respectively and corresponding lower limits on N_{int} were 15, 13 and 19 nucleons in iron interaction with air. We shall denote this fraction as $\mathcal{R}_h = N_{hot}/N_{int}$. Thus in the case of $\mathcal{R}_h = 0.1$ just two nucleons can melt and for values 0.2 and 0.4 this minimum is 3 and 8 nucleons respectively. The aim was to keep minimal N_{int} leading to QGP production above 10 nucleons. In the process of simulation N_{hot} nucleons are taken aside and the rest of particles participates further in collision simulated by VENUS code. The total energy of N_{hot} nucleons, E_{hot} is used to produce again N_{hot} nucleons, but this time with kinetic energy generated according to Boltzmann distribution isotropically in the overall centre of mass system. The remaining E_{hot} is used for production of $\pi^{\pm}$ and π^{0}, again with Boltzmann distributed kinetic energy and isotropically in the centre of mass system. The pion production is stopped when the E_{hot} decreases to the value 2.5 GeV. Afterwards this remnant cluster is passed to CORSIKA to further processing. In case of all the three above mentioned percentages the pions were generated with Boltzmann distribution parameters corresponding to the mean pion momenta $< p^{\pi} >$ value 60 MeV, 120 MeV, 300 MeV and 1 GeV respectively. The wide range of N_{hot} fraction values together with variety of possible mean momenta of generated pions are intended to offset uncertainties in description of the QGP freeze out. The properties of eventual QGP formed in light nuclei interactions are also unknown. For example the temperature might be not high enough to produce $c\bar{c}$ or even $s\bar{s}$ quark pairs. Also the isotropy of pions radiated during the freeze out is not guaranteed and the mean momentum along the shower axis may differ from momenta in the transversal plane and the numbers of produced pions thus might vary significantly. The mean numbers of pions produced at different conditions in this simple approach are given in the Table 1.

All the compared and tested data sets were generated as 2000 iron initiated showers with the primary energy within the range $10^{15}\ eV - 2.\ 10^{17}\ eV$ (the upper limit is the one recommended as a limit of reliability of the VENUS program [2]) and the spectral index of the energy distribution was -2.7 [7]. The primary zenith angle was fixed to value 0 deg while the azimuth angle and the altitude of the initial interaction were left free.

3. Quark Gluon Plasma Effects

The main detected quantities used to describe extended air showers are the electromagnetic and muon size and corresponding lateral distribution functions (LDF). These quantities are related as follows (e.g. for muons)

$$N_\mu = \int_{r_1}^{r_2} 2\pi\rho_\mu(r)dr,$$

where $\rho_\mu(r)$ is the density of particles (LDF) in the detection plane and $r = 0$ corresponds to the shower centre.

About one third of pions originating from QGP are π^0. Their decay products undergo further interactions in the atmosphere and they will disperse among other particles of electromagnetic nature. As the electromagnetic size is typically much bigger than the muon size, the QGP effects should be easier to detect in the muon component of extended air showers. However, the muon sizes of showers at the ground level do not reveal any differences. The truncated muon sizes N_μ^{tr} are compared in Fig. 1. The truncation corresponds more realistically to experimental conditions where the measurements at the shower core are hampered by systematics given by punch through and depend on the details of detector construction. The used pion kinetic energy cutoff is $E_{kin} > 300\ MeV$. The results of QGSJET and VENUS only are compared with simulations of QGP supplemented by VENUS in the case of the most abundant pion production, i.e. 40 % of N_{int} nucleons melting down and pions evaporating with mean momentum $60MeV$ - henceforth we shall abbreviate this as $QGP(0.4, 0.06)$.

Even the more detailed lateral distribution functions in Fig. 2 are almost identical and do not reveal any features which would allow us to observe effects corresponding to QGP formation. The events with QGP have slightly higher LDF values in the region $50 \div 100$ meters than the VENUS simulation. However, this difference is unmeasurable and the differences between QGSJET and VENUS are bigger than any QGP effects. The differences for events with other values of $\mathcal{R}_h$ and $< p^\pi >$ are similar or even smaller.

As a consequence of kinematics, the muons originating from QGP formed in the initial interaction of iron nucleus with air have mostly higher energies than the rest. In average they have momentum 280 GeV but the distribution has a very long tail. Thus detection of hard muons in the core of the extended air showers should reveal differences between cases with and without QGP production. To assess this, the data are further analysed as if detected at a medium depth underground. Our somewhat simplified virtual experiment is placed at the depth of 110 m with 100 m thick overburden made of standard rock ($A = 22, Z = 11$ and $\rho = 2.65g/cm^3$). The underground cavern with the ceiling 10 m high is supposed to have the detection area $100 \times 100\ m^2$. The tracing of the particles generated by CORSIKA through the rock was done by GEANT [8]. The rock filters out the muons with momenta smaller than 53 GeV.

The underground event muon size N_μ^u (necessarily truncated by the shape of experimental area at the outer limit) reveals notable differences already in the case of unmodified models (Table 2). The value used to define the tail of the underground muon size distribution - 990 muons, has been chosen so that in the case of pure VENUS simulations 400

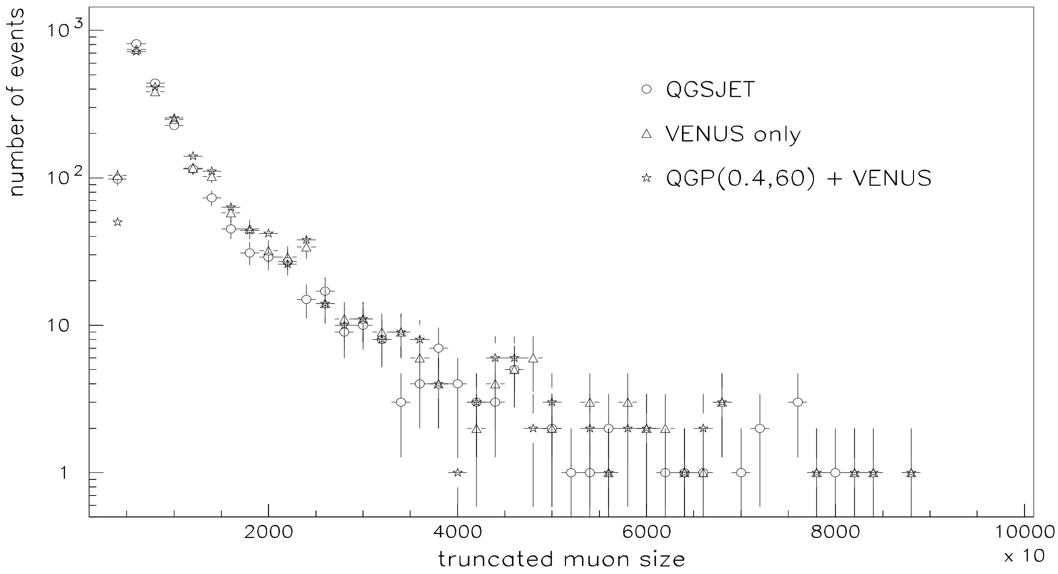

Figure 1: Muon size truncated between 30 and 230 meters from the shower centre at the ground level.

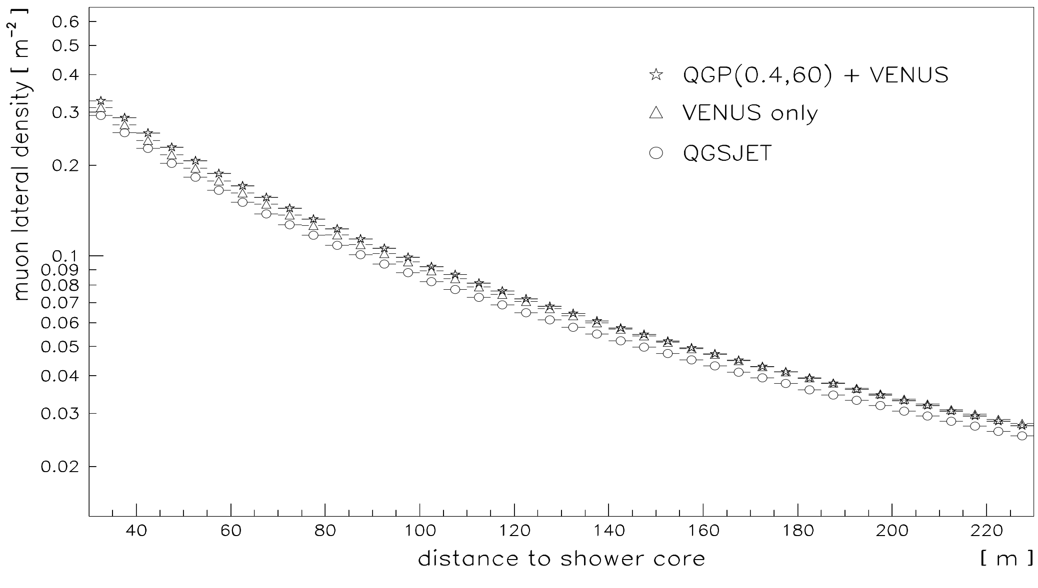

Figure 2: Lateral muon densities at the ground.

model	average N_μ^u	fraction of events with $N_\mu^u > 990$ (in %)
VENUS p	464	6.3 $\pm$ 0.6
QGSJET p	378	3.7 $\pm$ 0.4
VENUS Fe	807	20.1 $\pm$ 1.1
QGSJET Fe	709	13.6 $\pm$ 0.9
QGP(0.1,0.06)	849	21.8 $\pm$ 1.2
QGP(0.1,0.12)	843	21.7 $\pm$ 1.2
QGP(0.1,0.3)	829	20.4 $\pm$ 1.1
QGP(0.1,1.0)	819	20.4 $\pm$ 1.1
QGP(0.2,0.06)	868	23.4 $\pm$ 1.2
QGP(0.2,0.12)	871	22.9 $\pm$ 1.2
QGP(0.2,0.3)	867	22.5 $\pm$ 1.2
QGP(0.2,1.0)	809	19.3 $\pm$ 1.1
QGP(0.4,0.06)	967	27.0 $\pm$ 1.3
QGP(0.4,0.12)	955	26.5 $\pm$ 1.3
QGP(0.4,0.3)	904	24.3 $\pm$ 1.2
QGP(0.4,1.0)	835	22.0 $\pm$ 1.2

Table 2: The average underground muon size N_μ^u of events and the fraction of events with $N_\mu^u > 990$. All QGP simulations were supplemented by VENUS.

events pass the limit and the statistical error is thus 5 %. The effects of QGP are clearly detectable when the fraction of melted nucleons becomes larger. The event muon size at medium underground depth reveals differences between VENUS and QGSJET already in the case of proton data. The underground muon LDF obtained from VENUS have systematically higher values both for iron nuclei and protons than those generated by QGSJET (Fig. 3). In all compared cases the statistical errors are smaller than the maker size. Apparently such underground experiment can essentially help to tune the models which is the indispensable condition for any further studies of chemical composition of cosmic rays and search for QGP effects in cosmic ray showers.

The underground muon LDF with QGP simulation differ to various extent from the reference LDF obtained from data simulated by VENUS code only. The Fig. 4 a)-d) show the underground muon lateral distribution functions corresponding to different values of the ratio $\mathcal{R}_h$ divided by the reference LDF. Each picture summarises the distributions with the same value of $< p^\pi >$. The functions correspond to the events with large underground muon size - $N_\mu^u > 990$, where the differences were most notable. The LDF of VENUS and QGSJET with the same condition $N_\mu^u > 990$ are much more similar than the overall LDF in Fig. 3 - within the statistical errors they practically coincide over the whole range $0 \div 55\ m$ and hence the differences caused by QGP production are in this sense model independent. The Fig. 4 a)-d) show that the effects of more abundant pion production caused by increasing $\mathcal{R}_h$ can be to certain extent offset by increasing $< p^\pi >$. Near the centre of shower both scenarios give similar results but at greater distances from the shower core the LDF with QGP contribution decrease slower than the reference one and start to differ. This 'point of depart' moves away from the shower centre with increasing $< p^\pi >$ and becomes more prominent with the increase of $\mathcal{R}_h$.

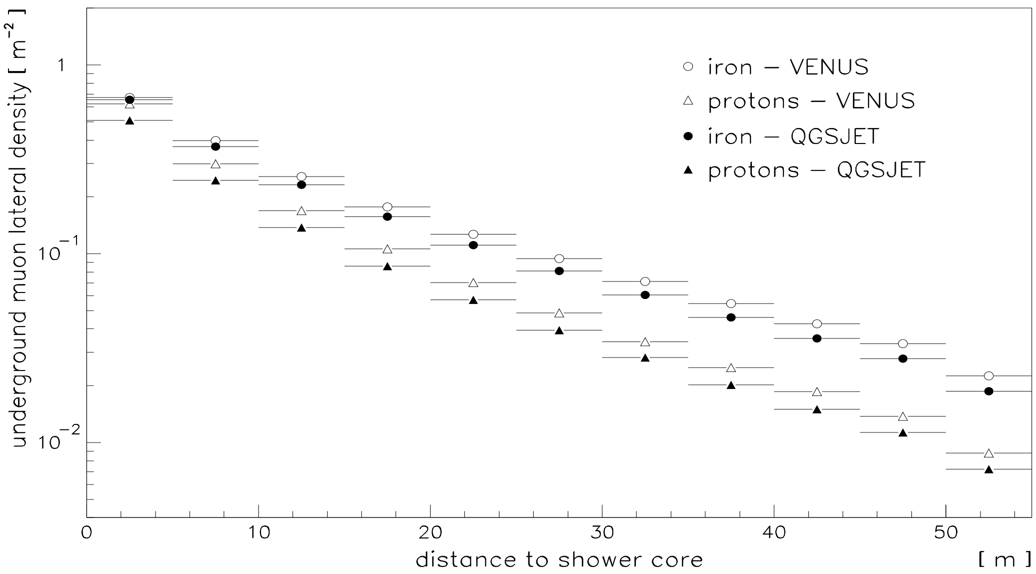

Figure 3: Underground lateral muon densities produced by VENUS and QGSJET.

As we are not dealing with the real data it is not urgent to increase the statistics to pinpoint exactly the values of $\mathcal{R}_h$ and $< p^\pi>$ at which the distinction between models with and without QGP still can be made. The compared LDF show that with the increasing $< p^\pi>$ one has also to increase the length at which the LDF can be measured in order to be able to see possible QGP effects. At small $\mathcal{R}_h$ one has to increase the observation time or the detection area to achieve the same effect. Thus in reality the resolution power of the experiment will be connected to the size of the available underground space.

4. Discussion

The simulated results cannot be currently compared with the real data as the experiments detecting extended air showers are either located at the ground and the high energy component is entirely drowned in the overall muon flux or, in case of the underground experiments, they are located so deep that the muon momentum cutoff is of the order of TeV or larger and only few muons penetrate to the detector ([9], [10], [11], [12], [13], [14]). The few experiments with medium overburden have either crude spatial resolution like the underwater experiments [15] and [16] or they have small detection area like [17] (6×16 m^2).

The whole study is based on the assumption that the conditions at the high energy interactions of cosmic rays with atmosphere can lead to the production of QGP states in the initial stage of the shower development. The inclusion of a very simple model of QGP production and freeze-out into high energy interactions of iron nuclei with the air in cosmic showers has shown that at certain kinematical conditions one could observe the QGP induced effects in the high energy muon component of the extended air showers. These kinematical conditions mean mainly sufficient available energy E_{hot} of melted nucleons and not too high mean momentum $< p^\pi >$ of the evaporated pions. The model has been for purpose chosen so simple that it can cover sufficiently large interval of the two

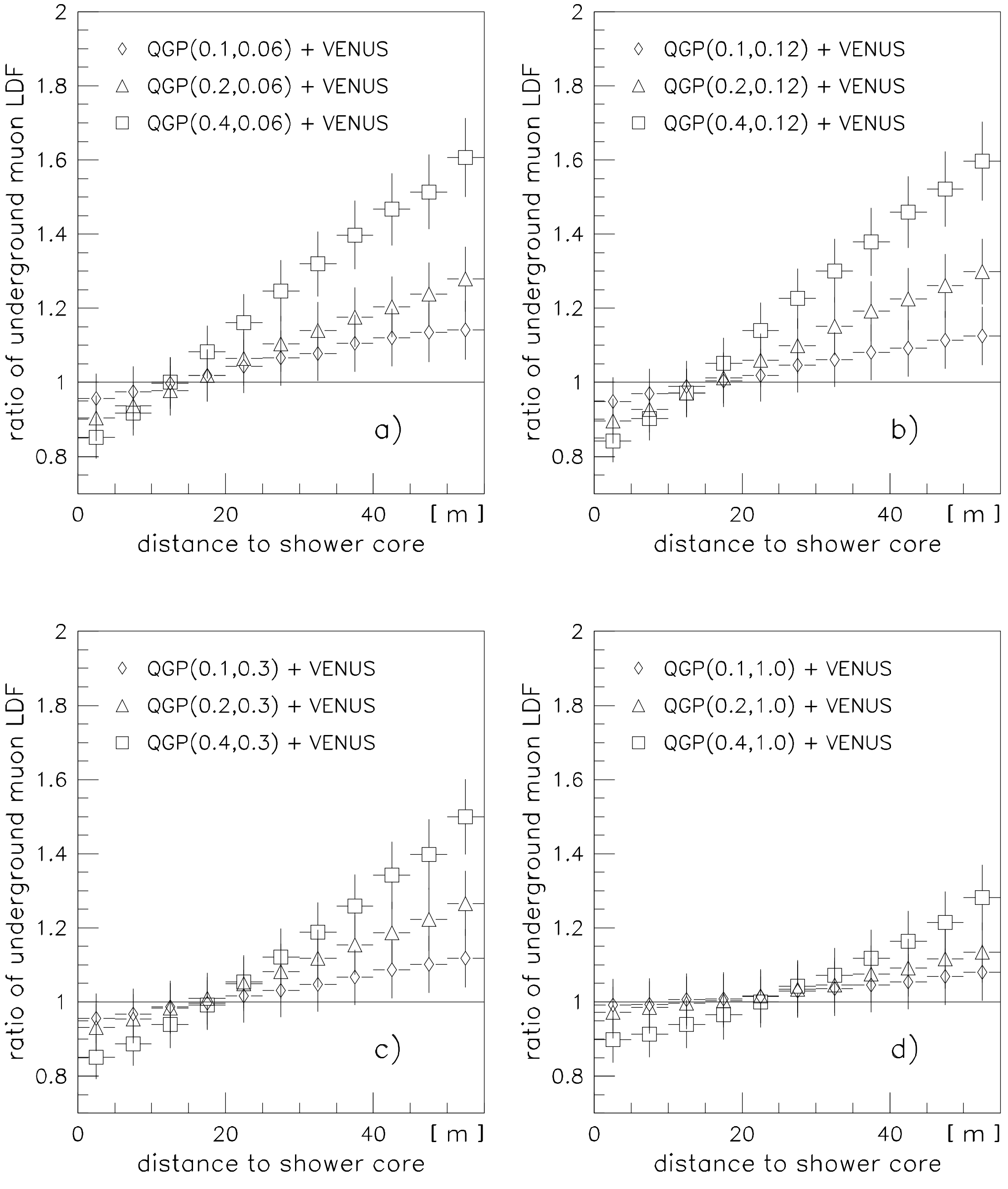

Figure 4: Ratio of underground lateral muon densities with QGP simulation to simulations done by VENUS only (events with $N_\mu^u > 990$).

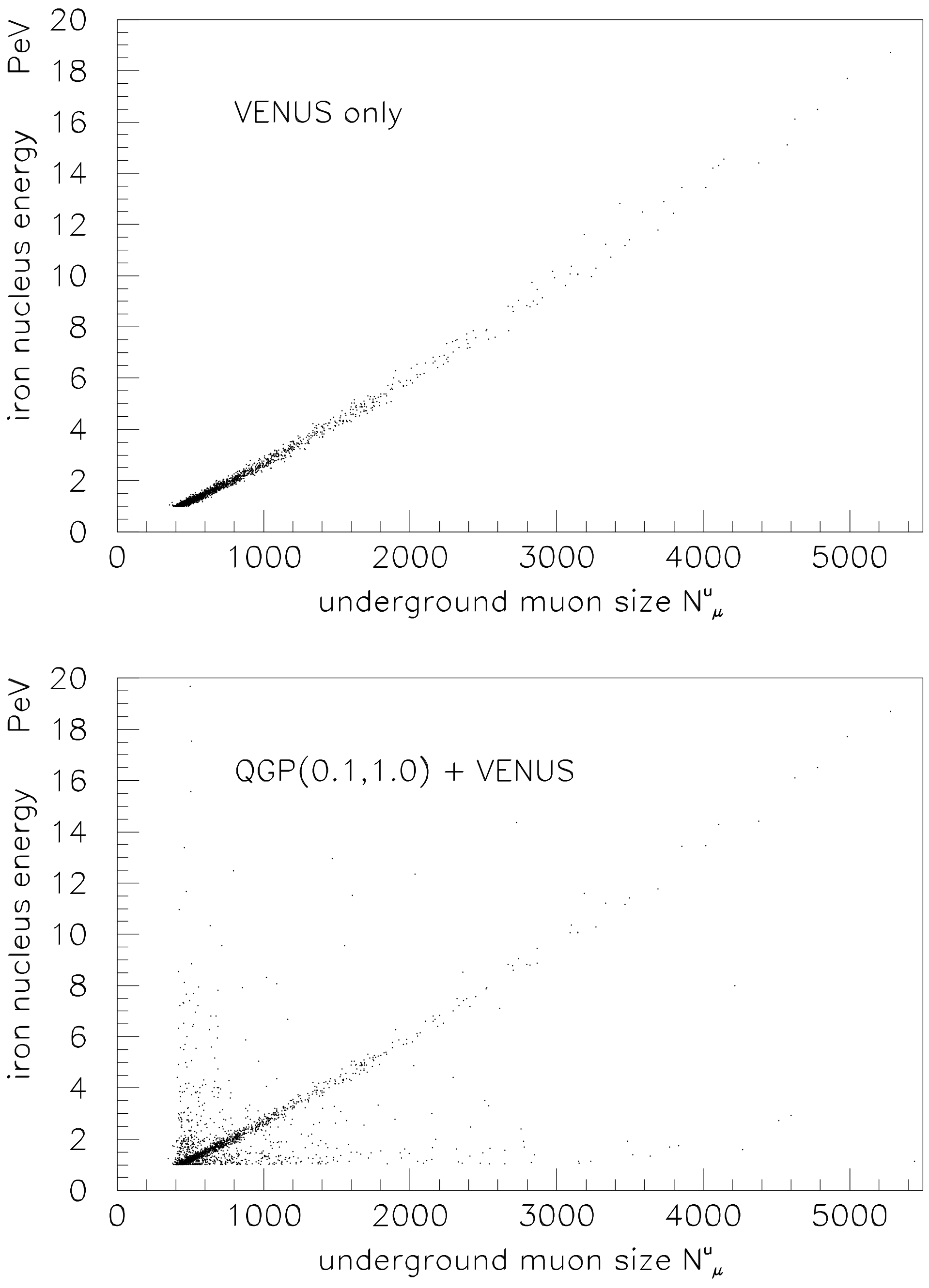

Figure 5: Underground muon sizes versus initial energy of iron nuclei.

above mentioned quantities with minimum parameters. It is interesting that none of the simulated QGP systems increases the muon density in the very centre of the shower and this number is determined by unmodified high energy interaction model - VENUS in this case.

Even in the situation when there is no apparent difference in the underground muon size N_μ^u or underground LDF like in the case of $QGP(0.1, 1.0)$ the QGP production can be still indicated provided the experiment would have an independent measurement of the ground muon size N_μ^{tr}. This quantity is proportional to the initial energy of impinging nucleus and the proportionality holds even underground (Fig. 5). Creation of QGP distorts the $energy - muon\_size$ balance and therefore comparison of the event muon size at the ground and underground can indicate deviation from standard scenario. The events under the diagonal of proportionality $E_{hot} \sim N_\mu^u$ are what one would expect - abundant pion production in QGP mimics the higher energy of the projectile nucleus. The events above the diagonal are more intriguing. Several factors contribute to their origin. One of them is that in normal interactions the leading particle effect constraints the lateral energy dissipation. No such effect has been included into QGP simulation and this combined with sometimes high altitude of primary interaction leads to spraying the QGP originated muons on a very large area. Another reason has to do with a deficiency of merging the hot nucleons with the rest. In order to keep the same energy spectrum of all compared simulations, the energy of the hot nucleons was subtracted from the initial generated energy value. As it was not possible to control the details of nucleus-nucleus interaction and to take into account the number of nitrogen/oxygen nucleons swallowed by iron nucleus, the energy subtraction was always done on the expense of the iron nuclei. This leads sometimes to larger decrease of the remnant interaction energy which appears as a decrease of corresponding part of the underground muon size.

The measurements of energetic muons in cosmic ray showers at medium depth underground can reveal information on the initial stages of the interaction otherwise inaccessible in the measurements at the ground. Provided the QGP can be formed in the light nuclei interactions, the number of produced muons will grow linearly with c.m.s. energy per nucleon. The ratio $\mathcal{R}_h$ should in naive expectations also grow with the energy and hence the observable effects are likely to became more apparent at higher energies. (In the used simple model $\mathcal{R}_h$ was considered to be energy independent.) Thus one should be in principle able to study some of the scenarios of QGP deflagration or detonation at the freeze out described in [18].

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References

[1] : Contribution to '26th International Cosmic Ray Conference' Salt Lake City, Utah, August 17-25, 1999.

[2] D. Heck *et al.*: CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers, Forschungszentrum Karlsruhe, Technik und Umwelt, Wissenschaftliche Berichte **FZKA 6019**, 1998.

[3] T. Antoni at al.:J. Phys. G, Nucl. Part. Phys. **25**(1999), 2161-2175.

[4] T.Antoni at al.: Electron, Muon and Hadron Lateral Distributions Measured in Air-Showers by the KASCADE Experiment, Astropart. Phys. **14**,(2001) 245-260.

[5] N.N. Kalmykov and S.S. Ostapchenko: Yad. Fiz. **56** (1993), 105. N.N. Kalmykov and S.S. Ostapchenko: Phys. At. Nucl. **56** (1993), 346. N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov: Bull. Russ. Acad. Sci. (Physics) **58** (1994), 1966.

[6] K. Werner: Strings, Pomerons and the VENUS model of hadronic interactions at ultrarelativistic energies, Phys. Rep. 232, Nos. **2-5** (1993), 87-299.

[7] K-H. Kampert *et al.*: Contribution to '26th International Cosmic Ray Conference', OG.1.2.11, Salt Lake City, Utah, August 17-25, 1999.

[8] R.Brun *et al.*: GEANT CERN Program Library Writeup W5013, 1993.

[9] MACRO Collaboration, M. Ambrosio *et al.*: Phys. Rev. **D** 52,(1995) 3793.

[10] SOUDAN Collaboration, Internal Report No.PDK-435, 1990 (unpublished).

[11] C.Castagnoli and O.Saavedra, Nuovo Cimento C **9**,(1986) 111.

[12] NUSEX Collaboration, M. Aglietta *et al.*: Proceedings of the topical seminar 'Astrophysics and Particle Physics', San Miniato, Italy, 1989, edited by G. Castellini *et al.* [Nucl. Phys. B(Proc. Suppl.) **14B**, (1990) 193.]

[13] LVD Collaboration, M. Aglietta *et al.*: Astropart. Phys. **3**,(1995) 311.

[14] Fréjus Collaboration, W. Rhode *et al.*: Astropart. Phys. **4**,(1996) 217.

[15] E.V. Bugaev *et al.*: Phys. Rev. **D** 58,(1998) 1.

[16] Yu.M. Andreyev, A.E. Chudakov, V.I. Gurentsov and I.M. Kogai: Proceedings of the 21st International Cosmic Ray Conference, Adelaide, Australia, January 6-19, 1990, edited by R.J. Protheroe (Dept. of Physics and Mathematical Physics, Univ. of Adelaide, Northfield, South Australia, 1990), Vol. **9**, p. 301.

[17] N. Ito (for the KGF Collaboration): Proceedings of the International Symposium on Underground Physics Experiment, Tokyo, Japan, 1990, edited by K. Nakamura (ICRR, Tokyo, 1990), p. 101.

[18] J. Cleymans, R.V. Gavai and E. Suhonen: Phys. Rep. Vol. 130, **4**,(1986) 217-292.