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The puzzle of muons: novel particles or novel properties

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Abstract. In order to examine a muon excess observed by the Pierre Auger Observatory, detailed Monte Carlo simulations were carried out, assuming the existence of strangelets (hypothetical stable lumps of strange quark matter) in the primary cosmic rays. We obtain a rough agreement between the simulations and the data for ordinary nuclei without any contribution of strangelets in primary flux of cosmic rays.

1. Introduction

Ultra-high energy ($E > 10^{18}$ eV) cosmic rays (UHECR) provide a formidable beam to study particle collisions at center-of-mass energies and kinematical regimes not accessible at terrestrial accelerators [1]. UHECR can only be observed indirectly, through air showers. The slant depth of the shower maximum X_{max} and the number of muons in an air shower N_{μ} are powerful tracers of the mass composition. Detailed simulations show dependences of both observables on hadronic interaction properties, such as multiplicity, inelasticity, charge ratio and baryon-antibaryon pair production [2, 3].

Over the past few decades, it has been suspected that the number of registered muons at the surface of the Earth is tens of percentage points higher than what it should be, according to existing hadronic interaction models [4, 5]. Recently, a study from the Pierre Auger Collaboration (Auger) has strengthened this suspicion, using a novel technique to mitigate some of the measurement uncertainties of earlier methods [5, 6]. The new analysis of Auger data suggests that the hadronic component of showers with primary energy $E > 10^{18}$ eV contains about 30% to 60% more muons than expected. Also the number of muons with energies above 0.75 GeV, determined by the Sydney University Giant Air-shower Recorder (SUGAR), exceeds the simulated one by the factors ~ 1.67 and ~ 1.28 for 10^{17} eV proton and iron primaries, respectively [7]. On the other hand, very recently, no muon excess in EAS has been reported [8]. To explain the muon excess, several new models have been proposed, exploring new physics [9, 10, 11] or new forms of matter, namely strange quark matter (SQM) [12]. Roughly, two possibilities arise: either we are dealing with novel particles or known particles have novel properties of multiparticle production processes.

In this paper we adopt a purely phenomenological approach to develop an SQM scheme. In sharp contrast to previous models our approach is based on the assumption that ultra-high energy cosmic rays are very heavy strange quark objects, i.e. strangelets. To examine this scenario in the shower development, as observed by the Pierre Auger Observatory, detailed Monte Carlo simulations were carried out.



2. Strangelets in cosmic rays

The analysis of the EAS data offers a unique possibility to observe possible imprints of strangelets arriving from the outer space. They are lumps of SQM, a new possible stable form of matter (cf. [13, 14, 15] for details). Following [16, 17] it is fully reasonable to search for SQM in cosmic ray experiments because the specific features of strangelets allow them to penetrate deep into the atmosphere [18]. The point is that there is a certain critical size of the strangelet, given by the critical value of its mass number $A = A_{crit} \simeq 300 - 400$, such that for $A > A_{crit}$ strangelets are absolutely stable against neutron emission. Below this limit strangelets decay rapidly evaporating neutrons. The spatial radii of strangelets turn out to be comparable to the radii of ordinary nuclei [16], i.e., their geometrical cross sections are similar to the normal nuclear ones. To account for their strong penetrability one has to accept that strangelets penetrating deeply into the atmosphere are formed in many successive interactions with the air nuclei by the initially very heavy lumps of SQM entering the atmosphere and decreasing due to the collisions with air nuclei (until their A reaches the critical value A_{crit} [16]). In this scenario the interaction of a strangelet of mass A with an air nucleus of mass A_{air} involves all quarks of the target located in the geometrical intersection of the colliding air nucleus and the strangelet. So, up to $3 \cdot A_{air}$ quarks from the strangelet could be used making its mass drop to a value of $A - A_{air}$.

There are several reports suggesting the existence of direct candidates for SQM (characterized mainly by their very small Z/A ratios). All of them have mass numbers A near or slightly exceeding A_{crit} . Analysis of these candidates for SQM show [16, 18, 17] that the abundance of strangelets in the primary cosmic ray flux is $F_{SQM}(A = A_{crit})/F_{tot} \simeq 2.4 \cdot 10^{-5}$ at the same energy per particle. For a normal flux of primary cosmic rays the expected flux of strangelets is then equal to $F_{SQM} \simeq 7 \cdot 10^{-6} \text{ m}^{-2}\text{h}^{-1}\text{sr}^{-1}$ for the energy above 10 GeV per initial strangelet.

The experimental data mentioned above lead to a flux of strangelets which is consistent with the astrophysical limits and with the upper limits given by the experiment [19]. The data follows the $A^{-7.5}$ behaviour, which coincides with the behaviour of abundance of normal nuclei in the Universe [17]. Interpretation of indirect observations (anomalous events observed in emulsion chambers, and also results from the measurements of EAS) can provide signals of strangelets. In particular, the excess of muon bundles has been observed by the ALICE detector at LHC, in its dedicated cosmic ray run [20] (confirming similar findings from the LEP era at CERN [21]). Arguing that muonic bundles of highest multiplicity are produced by strangelets, which are hypothetical stable lumps of strange quark matter infiltrating our universe, we successfully described data from CERN experiments [22]. All these considerations motivate further experimental search for the SQM and for its cosmological and elementary particle physics aspects.

3. EAS simulations

For the simulation of the propagation of extensive air showers in the Earth's atmosphere we have used a suitably modified SHOWERSIM [23] modular software. In our simulations we used the F00 model which consists in a simple non-scaling extrapolation of the inclusive data at ISR and SPS energies [24]. In this version, the leading particle remembers its charge, and the x -distribution of secondaries does not depend on the elasticity.

In the F00 model the identity of secondary particle is generated with the probability

$$p(x, E) = \alpha(x) + \beta(x) \ln(E), \quad (1)$$

where $x = p, \pi, K$ denotes various secondaries at 1 TeV. Probability of the emission of charged particle (π^\pm, K^\pm) is:

$$p(N_{ch}, E) = 1 - 0.5 [\alpha(K) + \beta(K) \ln(E)] - \alpha(\pi^0) - \beta(\pi^0) \ln(E). \quad (2)$$

In the standard version of F00 model $\alpha(\pi^0) = 0.3$, $\alpha(K) = 0.1$, $\beta(\pi^0) = 0.0128$, and $\beta(K) = 0.0028$. The fraction of produced neutral pions increase by 0.0295 per energy decade and fraction of produced kaons increases by 0.006 per decade. Changing the value of parameter β we can obtain a different number of charged particles, $\langle N_{ch} \rangle$ for a fixed number of secondaries, $\langle N \rangle = \text{const}$. In figure 1 we show the mean multiplicity of charged particles produced in proton-proton interactions as a function of the center-of-mass energy for our F00 model (full line). Again, EPOS LHC (dotted line) and QGSJETII-04 (dash-dotted line) predictions are taken from [25].

In the F00 model the inelasticity K , i.e. the relative energy used for production of secondaries, is sampled from a uniform distribution over an (0,1) interval for interacting nucleons and over an (0.333,1) interval for meson interactions. Therefore, the average inelasticity $\langle K \rangle = 0.5$ for nucleons and $\langle K \rangle = 0.667$ for mesons. In figure 2 we show the average inelasticity in proton-proton interactions as a function of the center-of-mass energy for our F00 model (full line). EPOS LHC (dotted line) and QGSJETII-04 (dash-dotted line) predictions are taken from [25].

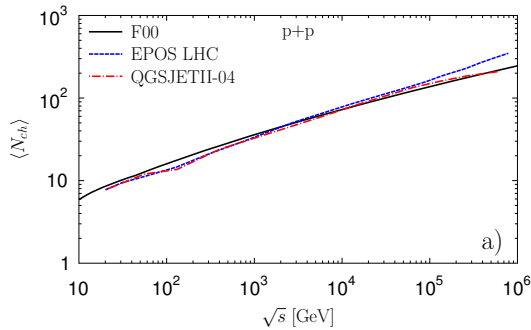


Figure 1. Mean multiplicity of charged particles produced in proton-proton interactions as a function of center-of-mass energy.

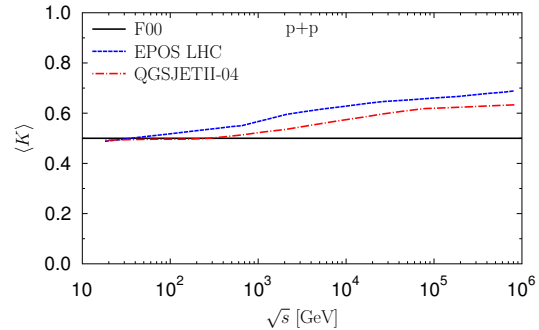


Figure 2. Average inelasticity in proton-proton interactions as a function of the center-of-mass energy.

For collisions with air nuclei, the inelastic cross-section dependence on energy is given by: $\sigma_{inel} = \sigma_0 + \delta \cdot [\ln(E/E_0)]^\alpha$ for $E \geq E_0$ and $\sigma_{inel} = \sigma_0$ for $E < E_0$, where $\alpha = 1.8$, $\sigma_0 = 280, 196, 178$ mb, $\delta = 2.5, 1.7, 1.6$ mb and $E_0 = 0.1, 0.067, 0.067$ TeV for primary nucleon, pion and kaon respectively.

In the development of EAS, the inelasticity K and the cross section for interactions σ are strongly correlated. The attenuation of hadrons or the depth of the shower maximum X_{max} are actually the measure of combinations of K and σ , and the effect of these two parameters is extremely difficult to disentangle. From the above we can see that $\langle K \rangle$ and σ_{inel} differ significantly for different models. Nevertheless, the $\langle X_{max} \rangle$ for these models are quite similar. The average positions of showers maxima as a function of primary energy are shown in figure 3. Obviously, the simulated values for different primaries follow a logarithmic trend, thus were fitted using the formula $\langle X_{max} \rangle = c + d \cdot \ln(E/10^{19} \text{ eV})$, with $c = 801.4, 724.3, 683.8$ and $d = 24.7, 28.0, 27.7$ for protons, iron nuclei and SQM, respectively.

The deep tail of the depth of maximum distribution, which has an exponential behaviour: $dN/dX_{max} \sim \exp(-X_{max}/\Lambda_X)$ and depends on the proton interaction length $\lambda \sim 1/\sigma_{inel}$ via shower maxima attenuation length: $\Lambda_X \simeq 0.8\lambda/\langle K \rangle$ [g/cm²]. Figure 4 shows the shower maxima attenuation length as a function of the center-of-mass energy for our F00 model (full line). EPOS LHC (dotted line) and QGSJETII-04 (dash-dotted line) predictions are taken from reference [25]. Despite the very different energy dependence of $\langle K \rangle$ and σ_{inel} , the shower maxima attenuation lengths Λ_X are very similar. We evaluate the attenuation of the showers

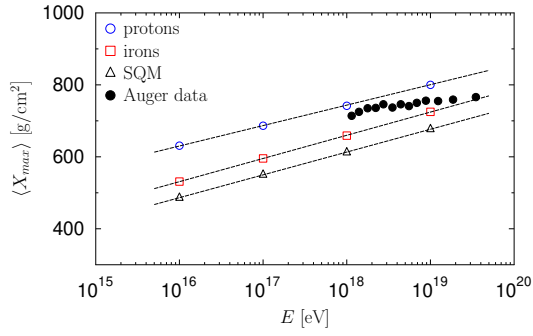


Figure 3. Average position of the shower maximum as a function of the primary energy for EAS generated by protons, iron nuclei, and SQM. Pierre Auger Collaboration measurements [26] are indicated by black circles.

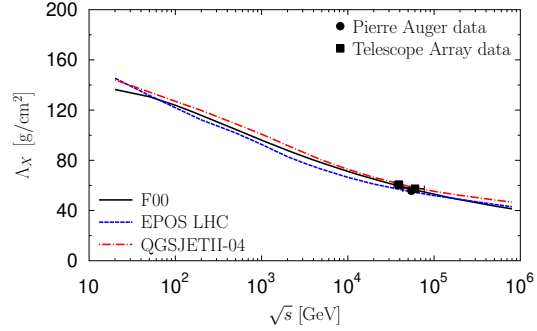


Figure 4. Attenuation length as a function of the center-of-mass energy. Pierre Auger Collaboration measurements [27] are indicated by black circles while Telescope Array data [28] by black squares.

maxima, Λ_X , for protons at 10^{18} eV obtaining $\Lambda_X = 58.5 \pm 1$ g/cm², which agrees nicely with the experimental data $\Lambda_X = 55.8 \pm 2.3$ g/cm² at $10^{18.2}$ eV, reported by the Pierre Auger Collaboration in [27], $\Lambda_X = 57.4 \pm 1.8$ g/cm² at $10^{18} - 10^{18.5}$ eV, and $\Lambda_X = 60.7 \pm 2.1$ g/cm² at $10^{17.8} - 10^{18}$ eV, given by the Telescope Array experiment [28].

We performed Monte Carlo simulations of the EAS generated by primary nuclei (protons and iron nuclei) and by primary strangelets with mass $A \geq A_{crit} = 320$ taken from the $A^{-7.5}$ distribution. In this study we have generated the inclined (primaries with zenith angle Θ from 60 deg to 80 deg were sampled) events with energies in the interval $10^{16} < E < 10^{19}$ eV. In the analysis we have focused on the muons in the nuclear cascade with energies larger than 0.3 GeV, which is the Cherenkov threshold for muons in water, reaching the Pierre Auger South Laboratory surface detector placed at the altitude 1425 m above sea level ($X_{atm} = 750$ g/cm²).

4. Results

In this section we provide a comparison of our SHOWERSIM simulations with the Pierre Auger Collaboration results presented in reference [5]. We focus at the showers generated with average zenith angles $\langle \Theta \rangle = 67$ deg. Following [5] the muon content R_μ is defined as:

$$R_\mu = \frac{N_\mu}{N_{\mu,19}}, \quad (3)$$

where N_μ is the total number of muons at the ground in EAS generated by primary cosmic rays at different primary energies, and the scale factor $N_{\mu,19}$ is the total number of muons in EAS generated by primaries with energy $E = 10^{19}$ eV. We used the power-law parametrization:

$$\langle R_\mu \rangle = a \cdot \left(E/10^{19} \text{ eV} \right)^b \quad (4)$$

with parameters $a = 1.841$ and $b = 1.029$ fitting Auger experimental events above $4 \cdot 10^{18}$ eV. At zenith angle $\Theta = 67$ deg the muon content $R_\mu = 1$ corresponds to $N_\mu = 1.455 \cdot 10^7$ muons at the ground with energies above 0.3 GeV. For model comparisons, as described in [5], the simulated number of muons should be then divided by $N_\mu = 1.455 \cdot 10^7$ to obtain R_μ , which can be directly compared to Auger measurements. In figure 5 we show the simulated muon content $\langle R_\mu \rangle$ of individual showers generated by primary protons, iron nuclei, and SQM, as a function

of the primary energy E together with the power-law fits (prepared using equation 4 with the parameters $a=1.5, 2.5, 3.2$ and $b=0.9, 0.9, 0.92$ for protons, iron nuclei, and SQM respectively). It is noticeable that Auger results are located between the simulation of protons and iron nuclei. The dependence of the average muon content $\langle R_\mu \rangle$ on the position of the showers maximum is

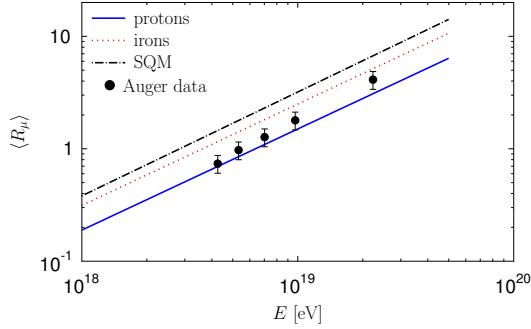


Figure 5. Average muon contents $\langle R_\mu \rangle$ of individual showers generated by primary protons, iron nuclei, and SQM, plotted as a function of the primary energy E , together with the Auger results taken from [5].

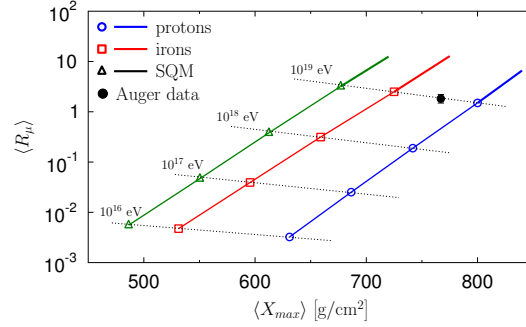


Figure 6. Average muon content $\langle R_\mu \rangle$ of individual showers generated by primary protons, iron nuclei, and SQM as a function of the average position of the shower maximum. The full circle shows the Auger result [5].

presented in figure 6. It is remarkable that no heavier component than iron is needed to describe the experimental values of $\langle R_\mu \rangle$ at 10^{19} eV. We can explain experimental data without strange quark matter.

The muon content in the air shower, R_μ , is a quantity related to the atomic mass A of the primary cosmic ray. A possible implication for the mass composition is demonstrated on the example, taking into account the obtained experimentally $\langle R_\mu \rangle = 1.82 \pm 0.38$ and the relative standard deviation $\omega = \sigma(R_\mu) / \langle R_\mu \rangle = 0.20 \pm 0.01$ [5]. For a single component, the values of ω can vary between $\omega = 0.04$ for pure iron nuclei and $\omega = 0.13$ for protons. More than two components (proton and iron) are needed to describe the first two moments of the R_μ distribution. The best description of the data is obtained with four components (40% protons, 20% helium, 35% nitrogen, and 5% iron nuclei) while the addition of more species does not improve the quality of the fit. The comparatively small abundance of iron nuclei has been evaluated from the analysis of the $\langle X_{max} \rangle - \sigma(X_{max})$ difference [29, 30]. Our results suggest roughly $\langle \ln A \rangle = 1.4$ with standard deviation $\sigma(\ln A) = 1.3$ at energies above $4 \cdot 10^{18}$ eV.

5. Concluding remarks

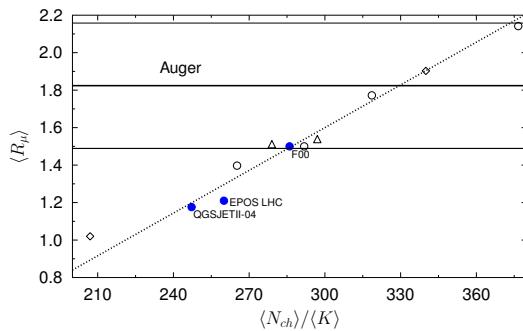


Figure 7. Average muon content $\langle R_\mu \rangle$ of showers generated by primary protons at 10^{19} eV plotted as a function of the ratio $\langle N_{ch} \rangle / \langle K \rangle$. The Auger result (with error band), indicated by a full line, is taken from [5]. The dotted line shows a linear fit given by equation 5. Open symbols show the results obtained for different modifications of $\langle N_{ch} \rangle$ in the F00 model.

Very surprisingly the F00 model included in the SHOWERSIM simulation package [23] describe nicely the muon content in EAS. Ordinary nuclei, without any contribution from strange quark matter in the primary flux of cosmic rays, can describe experimental data. Even if the strangelets contribute with a small amount in the primary flux and generate high multiplicity muon bundles, as we advocated recently [22], their influence on the average muon content $\langle R_\mu \rangle$ in EAS is negligible.

Apparently, our model differs from modern high-energy hadronic models such as EPOS LHC or QGSJETII-04, which cannot fit the experimental values of $\langle R_\mu \rangle$. Comparing different characteristics, we find that in the discussed models, $\langle R_\mu \rangle$ and the ratio of charged multiplicity to inelasticity $\langle N_{ch} \rangle / \langle K \rangle$ follow the same ordering. This is illustrated in figure 7. In addition to standard F00 model (shown by full circle) we present results for different modified $\langle N_{ch} \rangle$ according to equation 2 (shown by open symbols: circles correspond to different $\beta(K)$ and $\beta(\pi^0)$, triangles corresponds to different $\beta(K)$ and diamonds correspond to different $\beta(\pi^0)$). Roughly the number of muons depends linearly on the charged particle multiplicity:

$$\langle R_\mu \rangle = 0.0076 \langle N_{ch} \rangle / \langle K \rangle - 0.68. \quad (5)$$

We have shown in our simple model that we are able to reproduce the muon content in EAS. The charged particle multiplicity to inelasticity ratio seems to be crucial for understanding the muon excess. The muon component of EAS provides not only a powerful key for primary mass measurement but also provides information regarding hadronic interactions.

Acknowledgments

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