No muon excess in extensive air showers at $\sim 10^{17}$ eV primary energy: EAS–MSU muon versus surface detector data

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Abstract

Some discrepancies have been reported between observed and simulated muon content of extensive air showers: the number of observed muons exceeded the expectations in HiRes-MIA, Yakutsk and Pierre Auger Observatory data. Here, we analyze the data of the Moscow State University Extensive Air Shower (EAS–MSU) array on $E_\mu \gtrsim 10$ GeV muons in showers caused by $\sim 10^{17}$ eV primary particles and demonstrate that they agree with simulations (QGSJET-II-04 hadronic interaction model) once the primary composition inferred from the surface-detector data is assumed.

Keywords: extensive air showers, muon data, hadronic interaction models

1. Introduction

Ultra-high-energy cosmic rays provide for a unique laboratory to study hadronic interactions at the center-of-mass energies and in kinematical regimes not accessible at colliders. Modelling of the development of an extensive air shower (EAS), a cascade process in the terrestrial atmosphere initiated by an energetic cosmic particle, requires an extrapolation of verified interaction models. Not surprisingly, this often results in discrepancies between measured and simulated EAS properties, or between physical properties of
the primary particle reconstructed by different methods. A well-known result of this kind is the systematic difference between the primary energies $E$ reconstructed by the fluorescent detectors and by surface arrays for very same events, as seen by the Pierre Auger Observatory (PAO) [1] and the Telescope Array (TA) experiment [2]. It may or may not be related to the apparent excess of muons ($E_\mu \gtrsim$GeV in EAS reported at $E \gtrsim 10^{19}$ eV by the PAO [1, 3, 4] and Yakutsk [5] experiments. A similar excess had been observed earlier by the HiRes/MIA experiment at $E \gtrsim 10^{17}$ eV [6]. The purpose of the present study is to compare observed and simulated densities of $E_\mu > 10$ GeV muons in air showers induced by $E \sim 10^{17}$ eV primaries, based on the EAS-MSU data.

A subtle point of all comparisons of this kind is that the muon content of a EAS depends strongly on the type of a primary particle. As a result, the average muon content in the MC set depends not only on the hadronic interaction model used, but also on the primary composition assumed at the simulation. Therefore, for a meaningful comparison, one needs an independent estimator of the primary composition in the very same data set for which the muon data are analyzed. An estimator of this kind is often missing. In this work, we take advantage of the knowledge of the primary composition obtained from the surface-detector data only, as discussed below.

The rest of the paper is organized as follows. In Sec. 2 a brief description of the installation and of the data set is given, together with references to previous more detailed publications. In Sec. 3 we discuss the analysis performed in this work. Section 4 presents our results, while Sec. 5 summarizes our conclusions.

2. Data

Installation. The EAS-MSU array [7], located in Moscow, operated until 1990 in various configurations. A detailed description of the array in the ultimate configuration, whose data are discussed here, may be found in Ref. [8]. The total area of the array, 0.5 km$^2$, was covered with 76 charged-particle detector stations, each consisting of multiple Geiger–Mueller counters. A unique feature of the installation was the presence of large-area muon detectors. The main muon detector, located in the array center, had the total area of 36.4 m$^2$ and consisted of similar Geiger-Mueller counters, each with the area of 0.033 m$^2$, located at the depth of 40 meters of water equivalent underground. It is the data of this detector which we study here.
The geometry of the array, the trigger system and the reconstruction procedure are described in detail in Ref. [8]. The surface detector stations allow to reconstruct the lateral distribution function (LDF) for charged particles, parametrized as

$$\rho(S, r) = N_e C(S)(r/R_0)^{(S+\alpha(r)-2)} \cdot (r/R_0 + 1)^{(S+\alpha(r)-4.5)},$$

where $\rho$ is the particle density, $r$ is the distance to the shower axis, $R_0 = 80$ m is the Moliere radius, $S$ is the modified age parameter of the EAS, $C(S)$ is the normalization coefficient calculated numerically and $\alpha(r)$ is the correction to $S$ determined empirically and presented e.g. in Ref. [8], $0 \lesssim \alpha \lesssim 0.4$.

**Basic selection cuts.** The following cuts were imposed for the high-energy surface-detector data sample studied in this work:

1. Convergence of the reconstruction.
2. The LDF age parameter $0.3 < S < 1.8$.
3. The reconstructed zenith angle $\theta < 30^\circ$.
4. The reconstructed shower axis is within 240 m from the array center.
5. The reconstructed shower size is $N_e > 2 \times 10^7$, which corresponds to $E \gtrsim 10^{17}$ eV.

For this study, we use the data recorded in the period 1984 — 1990 (1372 days). After application of the cuts, the surface-detector data sample contains 922 events.

**Muon detectors.** The threshold energy of vertical muons registered by underground detectors [8] is $E_\mu \approx 10$ GeV. The main muon detector consisted of 32 independent sections. The muon density is estimated as $\rho_\mu = \ln (n/(n-m))/A$, where $n$ is the number of counters in the muon detector, $m$ is the number of fired counters and $A$ is the area of the counter. In our analysis, we further restrict the data sample to the days when not less than 28 of 32 sections were operational. This removes 20 days of data, so the final sample for muon studies contains 901 events.

3. Analysis

The muon density in an air shower decreases with the distance from the axis $r$, so to compare this quantity between data and MC, one often uses the LDF to recalculate the density to a particular fixed value of $r$. In this study,
we use $\rho_{\mu}(100)$, the muon surface density recalculated to $r = 100$ m with the help of the EAS-MSU muon LDF determined in previous works [9],

$$
\rho_{\mu}(r) = N_{\mu} \left( \frac{r}{R_0} \right)^{-0.7} \exp \left( -\frac{r}{R_0} \right).
$$

(2)

Comparison of the distributions in $\rho_{\mu}(100)$ for the real and simulated data constitutes the main part of this work. To produce a reliable simulation, we make use of the full Monte-Carlo (MC) model of the installation. This model, developed and described in detail in Ref. [8], accounts for the air-shower development in the atmosphere, its detection and reconstruction. The artificial events are recorded in the same data format as the real ones and are processed with the same reconstruction software. The resulting distributions of the reconstructed surface-detector parameters agree well between data and MC [8].

The muon density in air showers is a composition-dependent observable: heavier primary nuclei produce more muons. Many surface-detector observables are degenerate with respect to the primary composition, and a good description of data might, in principle, be achieved for various assumptions about the composition. That would lead to quite different predictions for the muon content, however. To perform a detailed comparison of muon data with simulations, one therefore requires the knowledge of the primary composition fully independent on muon detector readings. This is not always easy to achieve, and even in modern experiments, surface-detector composition studies are complicated and not very precise, see e.g. Refs. [10, 11]. Fortunately, the EAS-MSU setup provided for a required observable. Its surface array was very dense in its central part, and the slope of the LDF, parametrized by the age parameter $S$ in Eq. (1), is determined with a precision sufficient to distinguish between light and heavy primaries [8]. Indeed, an event in the sample we consider has, on average, 15 detectors used for the LDF reconstruction, which guarantees the required accuracy.

In Ref. [8], working in the frameworks of the two-component mixture of primary particles (protons and iron), we determined the best-fit composition which describes the surface-detector data, including the $S$ distribution. We use this mixture (43% protons and 57% iron) in MC simulations and obtain the expected distribution in $\rho_{\mu}(100)$ which we compare to that observed in the real data. Then, in order to quantify potential muon excess in data over simulations, we introduce the coefficient $k$ by which the muon number
is scaled in simulated showers. By definition, \( k = 1 \) corresponds to the muon number predicted in our simulations with the QGSJET-II-04 hadronic interaction model and with the determined above primary composition. By means of the binned likelihood method, we compare \( \rho_\mu(100) \) distributions derived for various \( k \) with the data and determine, consequently, the allowed range of \( k \). The scaling of the muon number was implemented only for muon density measured by underground detectors, but not for the surface-detector observables. We discuss the justification for this assumption in Appendix.

4. Results

Figure 1 compares the distributions in \( \rho_\mu(100) \) obtained from the simulations described above (\( k = 1 \)) and from the data. One may see that the distributions are in a good agreement.

To further quantify this agreement, one may proceed in two ways. Firstly, note that the muon content depends strongly on the assumed primary composition, see Fig. 2(a). We find the proton/iron mixture which describes the \( \rho_\mu(100) \) distribution as (52 ± 4)% iron, see Fig. 2(b) for the best fit, which agrees with 57% iron determined from the surface-detector data at the 90% CL.

Secondly, we study how the scaling of the muon number, that is the variation of \( k \), affects the agreement between data and simulations for the
Figure 2: Distribution of $\rho_\mu(100)$ in the data sample. Points with error bars: data. (a) green dashed histogram: MC, protons; red full histogram: MC, iron; (b) orange histogram: MC, best-fit primary composition inferred from these muon data (48% protons and 52% iron).
$\rho_\mu(100)$ distribution. This comparison is illustrated in Fig. 3 where the normalized binned likelihood is presented as a function of $k$. The standard statistical analysis results in $k = 0.93 \pm 0.04$, so that no muon excess in data is observed and $k = 1$ agrees with the data at the 90\% CL.

The main result of the paper is based on the primary composition derived from surface-detector data for the same data set. We tested its stability with respect to relaxing this assumption. Assuming the p/Fe mixture fitted to the KASCADE-Grande data [12] (59\% iron), we obtain $k = 0.92 \pm 0.04$; for Tunka-133 [13] (51\% iron) it is $k = 0.99 \pm 0.04$.

5. Conclusions

We have analyzed the number of muons ($E_\mu > 10$ GeV) registered by underground detectors of the EAS-MSU experiment. Starting from the Monte-Carlo simulation based on the primary composition inferred from the surface-detector data alone and on the QGSJET-II-04 hadronic interaction model, we obtain a good agreement between the simulations and the data. Assuming that the number of muons in air showers scales with a coefficient $k$ with respect to the simulation, we constrain $k = 0.93 \pm 0.04$, so that no muon excess ($k > 1$) is observed and $k = 1$ agrees with the data at the 90\% confidence level. Similar conclusions are obtained for primary composition assumptions favoured by the results of other experiments.
We note that the nice agreement between predicted and observed muon numbers reported here does not necessarily mean that QGSJET-II-04 gives a correct description of the muon production in any case. The agreement observed here relates to $E \sim 10^{17}$ eV, $E_\mu \gtrsim 10$ GeV and inner parts of the shower, $r \sim (2 - 3)R_0$. Previous results, collected in Table 1, have been obtained in various different regimes. The muon excess reported in Refs. [1, 3, 4, 5] (PAO, Yakutsk) was observed at primary energies $E \gtrsim 10^{19}$ eV and muon energies $E_\mu \gtrsim 1$ GeV. HiRes-MIA [6] observed the excess for $E_\mu \gtrsim 0.85$ GeV at $10^{17}$ eV $\lesssim E \lesssim 10^{18}$ eV. At the same time, recent preliminary IceTop results [14] for GeV muons and $10^{15} \lesssim E \lesssim 10^{17}$ eV suggest that no excess is seen. One should not forget also the important difference between our work and all these studies: here we investigate the inner parts of EAS, $\sim (2 - 3)R_0$, while the results of other experiments refer to the outer parts, $\sim 10R_0$. Note that at even lower $E$ and higher $E_\mu \gtrsim 1$ TeV, the muon excess may be probed with the help of atmospheric muons [15], and it has been reported [16] that QGSJET-II-04 overestimates the number of muons in this regime. Preliminary results of the KASCADE-Grande experiment at $E \sim 10^{17}$ eV suggest [17] that the atmospheric attenuation of the muon number is underestimated by all available hadronic models, including QGSJET-II-04. Clearly, further experimental and theoretical studies are required to understand the origin of the reported discrepancies and to arrive at a successful model of the air-shower development.

**Appendix A. Muon number scaling and the surface detectors**

The scaling of the muon number in our Monte-Carlo simulations was implemented for underground detectors, but not for the surface-detector ob-

| Experiment           | $E$, eV | $E_\mu$, GeV | $r/R_0$ | muon excess |
|----------------------|---------|--------------|---------|-------------|
| HiRes-MIA [6]        | $10^{17} - 10^{18}$ | $\gtrsim 0.85$ | $\gtrsim 10$ | +           |
| PAO [1, 3, 4]        | $\gtrsim 10^{19}$  | $\gtrsim 1$  | $\gtrsim 10$ | +           |
| Yakutsk [5]          | $\gtrsim 10^{19}$  | $\gtrsim 1$  | $\gtrsim 10$ | +           |
| IceTop [14]          | $10^{15} - 10^{17}$ | $\gtrsim 1$  | $\gtrsim 10$ | -           |
| EAS-MSU (this work)  | $10^{17} - 10^{18}$ | $\gtrsim 10$ | 2 − 3    | −           |

Table 1: Comparison with previous studies of the muon excess (see the text for notations and discussions).
servables. This assumption was tested by the analysis of surface-detector observables in the Monte-Carlo showers with downscaled number of muons. The downscaling itself is a random removing of a \(1 - k\) fraction of muons from the CORSIKA showers. Comparing the showers with \(k = k' \equiv 0.6\) and \(k = 1.0\), we found the mean change in the reconstructed \(N_e\) of 2.5%. The root mean squares of variations of the principal observables (primed quantities correspond to \(k = k'\)) are: \(\sigma((N'_e - N_e)/N_e) = 12.5\%\), \(\sigma(s' - s) = 0.047\), \(\sigma(R' - R) = 2.6\ m\), \(\sigma(\theta' - \theta) = 0.32^\circ\). We should note that the downscaling of muon number affects the SD observables stronger than its upscaling, so the presented values of variations can be considered as upper limits on what we can get with the upscaling of the muon number. At the same time, these values are smaller than the experimental uncertainties, see Ref. \[8\], therefore we can neglect the impact of the muon-number scaling on surface-detector observables.

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