Extensive air shower measured parameters and the possibility to obtain the UHECR mass composition

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Abstract

In this paper, a slope parameter of the lateral distribution function for charged particles in EAS is considered as a possible indicator of the type of a primary particle initiating the shower. Simulation result within the frameworks of different hadron interaction models are compared to experimental results obtained at the Yakutsk EAS array.

1 Introduction

Ultra-hight energy cosmic rays (UHECR) mass composition is very important for the problem of searching for their origins. There are several techniques for its estimation used in different experiments, including direct $X_{\max}$ observation by fluorescent light from the shower (HiRes, PAO) and analysis of the time-related parameters of the shower front.

Until recently, the Yakutsk EAS array didn't have differential particle detectors, allowing registration of a shower front structure or a direct longitudinal development observation and it's not always possible to reconstruct $X_{\max}$ by Cherenkov light flux [1, 2] since not all showers do feature a Cherenkov light data. A large amount of EAS data that has been accumulated since 1970$^{\text{ths}}$ is still to be analysed and properly interpreted.

In this paper we are looking for possibilities to obtain plausible mass composition estimation using EAS parameters directly measured in the Yakutsk experiment. To obtain a connection between them we used a library of showers simulated with the `CORSIKA` code [3] built with different hadron interaction models and results were compared to the experimental data.

2 Simulation

The main EAS charged component parameter measured at the Yakutsk EAS array is particles density at the core distance 600 m — $\rho(600)$. In our experiment a Greisen-Linsley approximation [2, 4] was adopted for treating the charged particle lateral distribution function (LDF):

$$\rho(r) = N_s \cdot \left(\frac{r}{r_0}\right)^a \cdot \left(1 + \frac{r}{r_0}\right)^{b-a}, \tag{1}$$

where N_s is a shower size parameter, r_0 — Moliére radius (determined by the atmospheric parameters) and $a = -1$. During the event processing, b is treated as a $\rho(600)$ and zenith angle dependency:

$$b(\theta, \rho(600)) = -1.38 - 2.16 \cdot \cos\theta - 0.15 \cdot \lg\rho(600), \tag{2}$$

obtained by the so-called *mean LDF* method [5].

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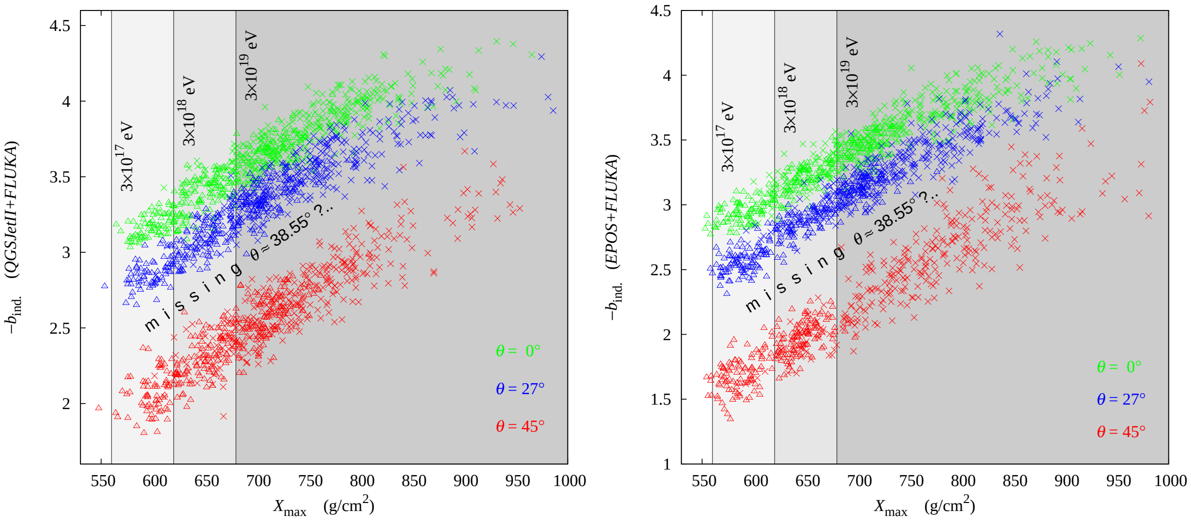

Figure 1: Slope parameter b vs. $X_{\max}$ in individual showers. Triangles correspond to iron-induced showers, crosses — to proton-induced showers. Left side — QGSjetII, right — EPOS. Low energy hadronic model — FLUKA [6]

As it was stated before, there is no way of a direct $X_{\max}$ observation, but it is always possible to calculate b parameter of LDF in individual showers, which can be roughly related to longitudinal development features of the shower.

To estimate regularities in b, a set of showers was simulated for two kinds of primaries (proton and iron), for five values of a primary energy ($E_0 = 3 \times 10^{17}$, 9.5×10^{17}, 3×10^{18}, 9.5×10^{18} and 3×10^{19} eV, corresponding to effective energy range of our experiment) and for four values of zenith angle ($\theta = 0°$, $27°$, $38.55°$ and $45°$); 100 events for each set of parameters. Simulation was performed using CORSIKA code (version 6.710), within the frameworks of two high-energy hadron interaction models (QGSjetII-03 [7] and EPOS [8]). In order to reduce computation time, the simulation was performed with activated thinning mechanism ($thin = 10^{-5}$, $\omega_{\max} = 10^{10}$).

For every shower, a radial binning with logarithmic step was performed. In each bin a direct particle density was calculated as $\rho(r_k) = \sum_i^n \omega_i / s_k$, where ω_i — particle weight, s_k — area of a k_{th} bin. For charged component, a sum of muons and electrons was calculated as $\rho(r_k) = \sum_i^n (\omega_i^e + \omega_i^\mu)/s_k$, where muons threshold energy $\varepsilon_{\rm th} \leq 1 \cdot \cos\theta$ were selected.

In the initial tests, a correlation between $X_{\max}$ and b was pointed out (see fig. 1). However, as it can bee seen from fig. 1, it is quite difficult to distinguish between two different primaries even for fixed given energies; when it comes to experimental data, uncertainties in the energy estimation (as well as in zenith angle determination) would result in more complicated and fuzzy picture.

But it is possible to exclude the need in $X_{\max}$ estimation at all, if one takes into account the difference in the slope parameter distribution for different primaries. From fig. 2 it is seen, that showers initiated by lighter nuclei have more steeper LDF, than those initiated by heavier ones. It is also seen, that proton-induced showers have a wider b distribution.

3 Comparison with the experiment

As there is some dispersion in $\rho(600)$ for given E_0 and θ, showers should be selected by $\rho(600)$ in a narrow zenith angle interval, or at least a zenith-angular dependency of b should be excluded.

For each set of (E_0, θ), a mean LDF in the form of (1) was fitted with $\rho(600)$ and b as free parameters. The result is shown on fig. 3 in comparison to the dependency used in the Yakutsk experiment, expressed by (2). It follows from the comparison, that there is a disagreement between the both models and the experiment. In particular, it appears that simulated showers demonstrate stronger zenith-angular

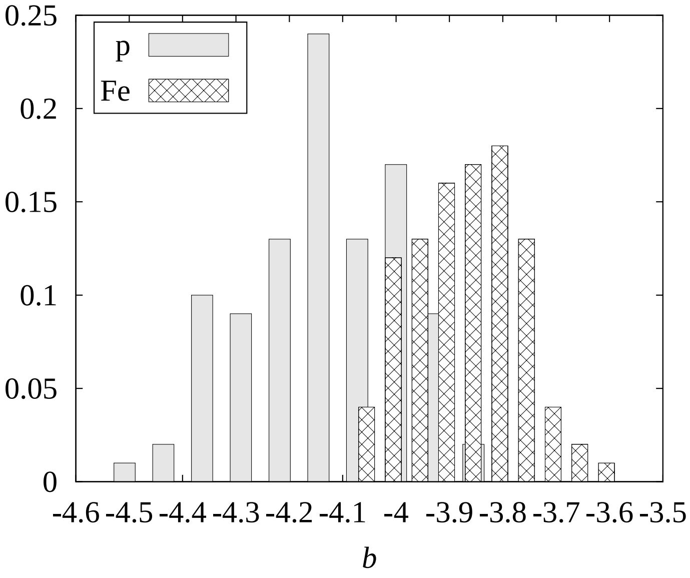

Figure 2: A normalized histogram of b values for two primaries. 100 events, `QGSjetII` + `FLUKA`, $\theta = 27°$, $E_0 = 3 \times 10^{18}$ eV.

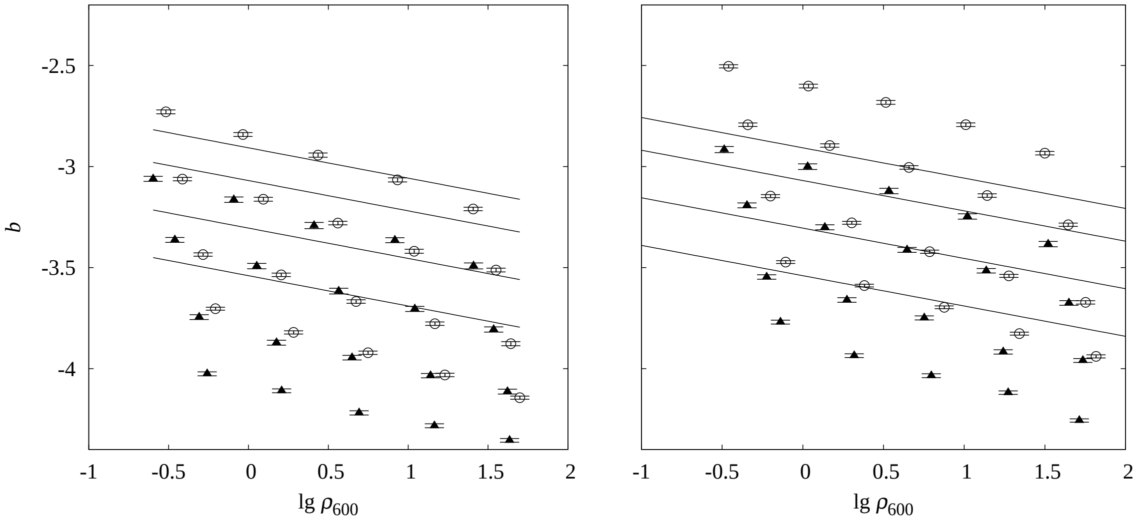

Figure 3: A $\rho(600)$ and θ dependency of b obtained in simulation (triangles — p, circles — Fe) compared to the dependency used in the Yakutsk experiment (lines), see (2). Left — `QGSjet II` + `FLUKA`, right — `EPOS` + `FLUKA`. Zenith angle increases in upward direction: 0, 27, 38.55 and $45°$

dependency of the LDF slope parameter, than measured in the experiment; the $\rho(600)$ dependency is also stronger in simulated showers.

This divergence could be explained in several ways. The most obvious — particle density measured in our analysis is in fact the *actual particle density*, i.e. number of particles per radial bin, not the detector response. As it was shown in the work by L. G. Dedenko et al, the contribution from secondary γ-photons to energy deposit measured by the detector should increase along the core distance [9]. Other possible fact that could influenced upon the obtained result is that in the Yakutsk experiment, only a part of core distance range is covered: for energy $\sim 10^{17}$ eV it is $\sim 50 - 600$ m, for middle energy range $\sim 10^{18}$ eV it is $\sim 600 - 1000$ m, for ultra-high energies $\sim 10^{19}$ eV — $800 - 2000$ m, and in simulation the whole core distance range ($\sim 50 - 2000$ m) was considered.

4 Conclusion

The simulations of EAS with the `CORSIKA` code have shown, that it is possible to distinguish between different kinds of primaries using LDF slope parameter b and particle density at fixed core distance $\rho(600)$, which are well measured in the Yakutsk experiment. However, a more detailed treatment of the simulated showers is required, including studying of the processes arising in the array detector during particle transition and even considering the geometry of the array itself.

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