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All-particle primary energy spectrum in the knee region

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We present the all-particle primary energy spectrum obtained by new 7-parametric event-by-event method of determination of the primary energy on the basis of EAS size (N_{ch}), truncated muon size $N_\mu(E_\mu > 5$GeV, $R < 50$m), shower age (s) and zenith angle (θ) parameters measured by the GAMMA facility at mountain level (700 g/cm^2). 7-parametric energy estimator was developed using the CORSIKA EAS simulation code with the QGSJET and SIBYLL interaction models, taking into account the response of GAMMA detectors and the reconstruction uncertainties of EAS parameters. We attained practically unbiased ($< 5\%$) primary energy estimations with accuracy about $15 \div 10\%$ in the $1 \div 100$ PeV energy range respectively.

1. Introduction

The mountain location of the GAMMA experiment and the agreement of observed and simulated data in the measurement range $5 \cdot 10^5 \leq N_{ch} < 10^7$ [1, 2, 3] allowed to obtained with high reliability the all-particle energy spectrum. The method is based on an event-by-event evaluation of the primary energy using reconstructed parameters $\tilde{N}_{ch}, \tilde{N}_\mu, \tilde{s}, \theta$ of detected EAS. Such possibilities have been studying for a long time in the different works [4, 5, 6] and a main difficulty is to obtain an unbiased energy estimation at an existent (but unknown) abundance of the primary nuclei taking into account the fluctuations of shower development and detector response.

2. GAMMA experiment

The main characteristic features of the GAMMA experiment [1, 4] are the mountain location (3200 m a.s.l.), symmetric disposition of the surface EAS detectors and underground muon scintillation carpet to detect EAS muon component at $E_\mu > 5$ GeV energies.
The ground based array consists of 33 surface particle detection stations disposed on 5 concentric circles of radii: 20, 28, 50, 70, 100 m. Each station contains 3 square plastic scintillation detectors with dimensions 1x1x0.05 m^3.The photomultiplier tube is positioned on the top of the aluminum casing covering the scintillator. One of the three station's detectors is examined by two photomultipliers, one of which is designed for fast-timing measurements [1].
150 underground muon detectors (muon carpet) are compactly arranged in the underground hall under 2.3 Kg/cm^2 of rock. The dimensions, casing and applied photomultipliers are the same as in the EAS surface detectors. The trigger condition provides EAS detection with the EAS size threshold $N_{ch} > (0.5 \div 1) \cdot 10^5$ at the location of the EAS core within the $R < 25$ m circle.
Unbiased ($< 5\%$) estimations of N_{ch}, s, x_0, y_0 shower parameters are obtained at $N_{ch} > 5 \cdot 10^5$, $\theta < 30^0$, and $R < 25$ m from the shower core to the center of the EAS array distances. Corresponding accuracies are derived from MC simulations by the CORSIKA(EGS) [7] and are equal to: $\Delta N_{ch}/N_{ch} \simeq 0.1$, $\Delta s \simeq 0.05$,

$\Delta x, \Delta y \simeq 0.5 \div 1$ m [2]. The reconstruction accuracy of EAS muon truncated ($R_\mu < 50$m) size is equal to $\Delta N_\mu/N_\mu \simeq 0.2 \div 0.35$ at $N_\mu \simeq 10^5 \div 10^3$ respectively [1, 2].
The EAS zenith angle (θ) is estimated on the basis of the measured shower front arrival times by 33 fast-timing surface detectors, applying the maximum likelihood method and the flat-front approach. The corresponding uncertainty are tested by MC simulations and is equal to: $\sigma(\theta) \simeq 1.5^0$.

3. Event-by-event analysis and all-particle spectrum

Using the simulated database [2, 3], $J = 1.5 \cdot 10^4$ EAS events were taken for each of $k = 1, \ldots, 4$ kinds (H, He, O, Fe) of primary nuclei and each interaction model (SIBYLL2.1 [8], QGSJET01 [9]). The details of EAS simulation by CORSIKA code taking into account detector response and electron (positron) accompaniment of muons in the underground muon hall are presented in [2, 3].
The reconstructed $\tilde{N}_{ch}, \tilde{N}_\mu, \tilde{s}$ shower parameters, known zenith angle θ and primary energy E_0 were used at minimization [2]

$$\chi^2(a_1, \ldots, a_p) = \frac{1}{4J - p - 1} \sum_{k=1}^{4} \sum_{j=1}^{J} \frac{(\ln E_{1,k,j} - \ln E_{0,k,j})^2}{\sigma_E^2} \tag{1}$$

where $E_1 = f(a_1, \ldots, a_p | \tilde{N}_{ch}, \tilde{N}_\mu, \tilde{s}, \theta)$ is the investigated parametric function with $a_1, \ldots, a_p$ parameters, $\sigma_E = 0.15$ is expected accuracy of the E_1 evaluated energy. The best estimations were achieved at 7-parametric

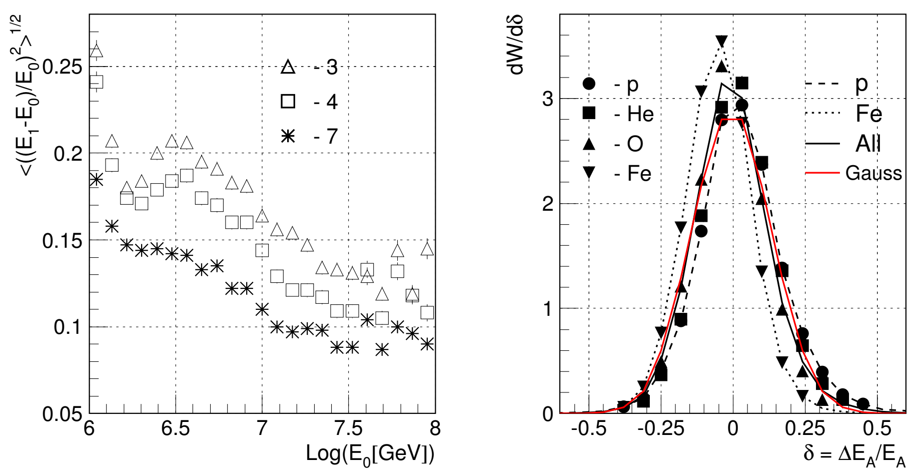

Figure 1. Accuracy (RMSD) of the primary energy evaluations at different number of approximation parameters (left panel) and distribution of errors of the primary energy estimation by event-by-event 7-parametric fit at different primary nuclei.

$(p = 7)$ fit:

$$\ln E_1 = a_1 x + \frac{a_2 s}{c} + a_3 + a_4 c + a_5 e^s + \frac{a_6}{(x - a_7 y)} \quad , \tag{2}$$

where $x = \ln \tilde{N}_{ch}$, $y = \ln \tilde{N}_\mu (R < 50m)$, $c = \cos\theta$ and energy E_1 has units of GeV. The values of the $a_1, \ldots, a_7$ parameters for both interaction models and the corresponding χ^2 obtained from (1) at $\sigma_E = 0.15$

Table 1. Approximation parameters $a_1, \ldots, a_7$ of primary energy evaluation (2) and corresponding χ^2, obtained from (1) at the SIBYLL and QGSJET interaction models.

Model	a_1	a_2	a_3	a_4	a_5	a_6	a_7	χ^2
SIBYLL	1.03	3.96	-4.24	1.99	-1.14	11.7	0.94	0.85
QGSJET	1.04	4.55	-4.97	2.51	-1.38	13.1	0.93	0.92

are displayed in Table 1. The root mean square deviations of the energy estimation by 7-parametric fit (2) in the framework of SIBYLL model is shown in Fig. 1 (left panel). The corresponding results at three (only $x, \tilde{s}$ variables) and 4-parametric $(x, \tilde{s}, \cos\theta)$ fits are shown in Fig. 1, as well.

The obtained error distributions estimating primary energy by 7-parametric approximation (2) are shown in

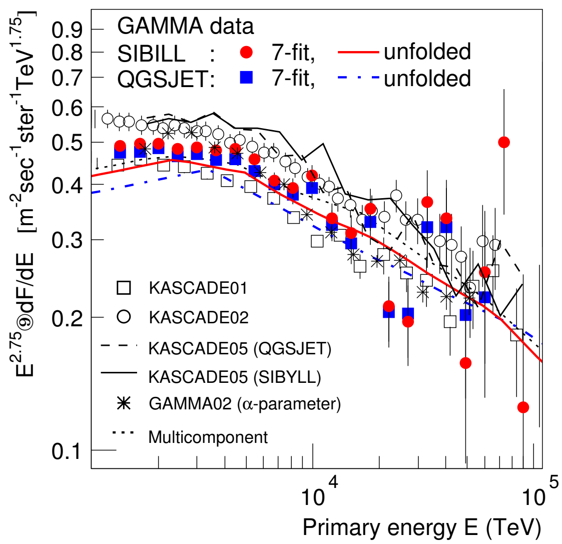

Figure 2. All particle primary energy spectra obtained by event-by-event 7-parametric analysis (filled red and blue symbols) and EAS inverse problem solutions (solid and dashed color lines) [2, 3] on the basis of GAMMA 2002-2004 database and parametrization of the primary energy spectra. The red (blue) symbols and lines correspond to the SIBYLL (QGSJET) interaction model. KASCADE data were taken from [12, 13] and obtained by unfolding of EAS inverse problem using iterative method [14].

Fig. 1 (right panel) for H, He, O, Fe nuclei. The red line corresponds to the Gaussian distribution at the same parameters as the cumulative distribution (solid line).

The all-particle energy spectrum derived on the basis of the GAMMA 2002-2004 EAS data set [2, 3] and fit (2), at the QGSJET (red filled square symbols) and SIBYLL (blue filled circle symbols) interaction models are shown in Fig. 2.

Notice, that the energy spectrum obtained by event-by-event method claims additional corrections, because the errors $\sigma_E = \sigma(\Delta E/E)$ and power-law energy spectra $(\sim E^{-\gamma})$ lead to an overestimation of the spectrum $\eta = \exp\left(((\gamma-1)\sigma_E)^2/2\right)$ times. Moreover, the inevitable biases of energy estimations $\epsilon(A) =< E_1/E_0 >$

depend on primary nuclei and shift the corresponding energy spectra $\beta(A) = \epsilon^{\gamma-1}$ times. The spectral shift due to $\beta(A) \neq 1$ impossible to take into account without information about abundance of primary nuclei.
The observed biases of 7-parametric fit (2) are distributed from $\epsilon(p) \simeq 1.02\%$ up to $\epsilon(Fe) \simeq 0.96\%$ (Fig. 1) and here are neglected. In the results shown in Fig. 2, the corrections of $\eta(E)$ are taken into account using the expected accuracies from Fig. 1.
The solid (red) and dashed (blue) lines in Fig.2 represent the all-particle primary energy spectra obtained on the basis of GAMMA data set by the solution of parametrized EAS inverse problem in the framework of the SIBYLL and QGSJET models respectively [2, 3]. The event-by-event analysis of the GAMMA data at the QGSJET interaction model using α-parametric method [4] also shown in Fig. 2 (asterisk symbols). The dotted line in Fig. 2 represents the parametrized solutions of the EAS inverse problem for the KASCADE EAS data at rigidity-dependent steepening primary energy spectra [10]. The results of KASCADE02 in Fig. 2 obtained by the non-parametric event-by-event analysis was taken from review [11]. The KASCADE01,05 data (iterative method [14]) were taken from [12, 13] respectively .

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