Tunka-Grande array for high-energy gamma-ray astronomy and cosmic-ray physics: preliminary results.

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Introduction

Tunka-Grande array:

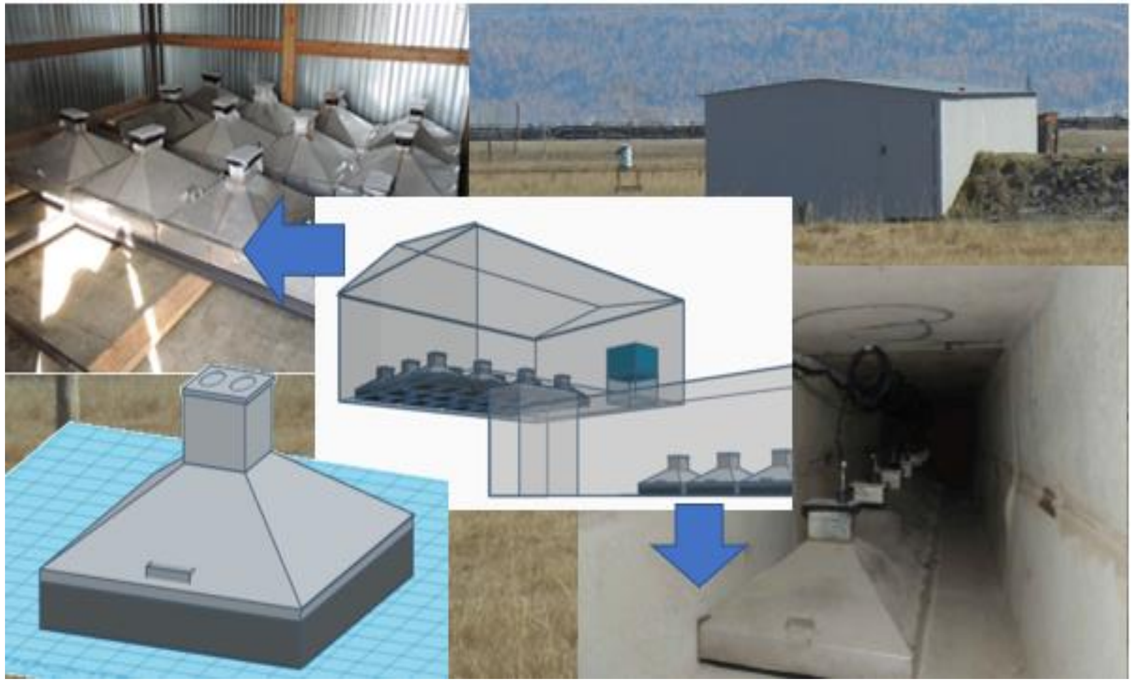
19 **Scintillation Stations** on area ≈ 0,5 km^2.

Scintillation Station = Surface detector + Underground detector ;

Surface detector =12 scintillation counters;

Underground detector = 8 scintillation counters.

- Scintillation counter area – 0.64 m^2.
- Surface detector area ~ 8 m^2.
- Underground detector area ~ 5 m^2.
- Distance between stations ~ 175 m.
- Altitude of 669 m a.s.l.



3 operation seasons:

During the three seasons from 2017 to 2020, there were 542 days of Tunka-Grande operation. The array trigger condition was a coincidence of any three surface detectors within 5 μs. During this period, about 2950000 triggering events were recorded on the Tunka-Grande area over 8080 h of operation. The scintillation array also operated using triggers of the Tunka-133 Cherenkov array. During the three seasons, there were 787 h of joint operations and about 252000 events were selected.

Reconstructing EAS parameters

Steps of reconstruction:

- Extraction of pulse amplitude A_i, front delay t_i, and pulse area Q_i..
- Shower core coordinates: $\boldsymbol{x} = (\sum_{i=3}^{k} \boldsymbol{\rho\_i} \cdot \boldsymbol{x\_i})/(\sum_{i=3}^{k} \boldsymbol{\rho\_i}), \quad \mathbf{y} = (\sum_{i=3}^{k} \boldsymbol{\rho\_i} \cdot \boldsymbol{y\_i})/(\sum_{i=3}^{k} \boldsymbol{\rho\_i})$,

where $\boldsymbol{k}$ – the number of triggered surface detectors, $\boldsymbol{\rho\_i}$ – particle density in surface detector.

- The shower arrival direction is determined by fitting the measured pulse front delay using a curved shower front formula, which is obtained in a Kascade-Grande experiment [1]: **Ti – Tth =a(1 + R$_i$/30)^b**, where Tth is the theoretical delay time for a flat shower front, R_i is the perpendicular distance from the shower axis in meters.
- The shower core coordinates, number of muons and charged particles, and slope of the LDF are calculated in minimizing the functional using independent variables.
- To reconstruct the lateral distribution of charged particles, the LDF from the EAS MSU experiment [2] is used.
- The lateral distribution of muons is described using the Greysen function with fixed parameters *a* and *R* and variable parameter *b* [2].
- As a measure of energy, we use the charged particles density at a core distance of 200 meters – ρ_{200}.

The parameter ρ_{200} is rescaled to the vertical direction relative to the measured zenith angle as:

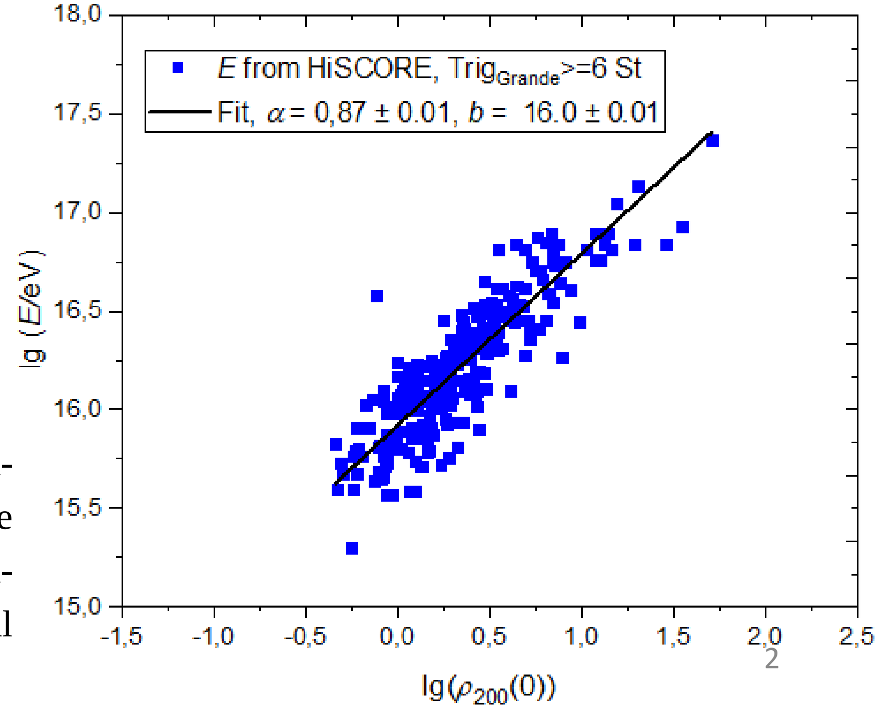
$$\boldsymbol{\rho_{200}(0) = \rho_{200}(\theta) \cdot e^{\left(\frac{x_0}{\lambda} \cdot (sec\,\theta - 1)\right)}},$$

where x_0 = 960 g/sm^2 is the atmospheric depth from sea level for the Tunka Valley,
λ = 206 g/sm^2 – obtained from experimental data average value of absorption path length.

- The value of $\rho_{200}(0)$ relative to the energy can be rescaled as: $\boldsymbol{E_0 = 10^b \cdot (\rho_{200}(0))^a}$,

where $a = 0.87 \pm 0.01, \; b = 16.0 \pm 0.01$.

Correlation $\rho_{200}(0)$ with the primary energy is determined using the experimental results of TAIGA-HiSCORE array. For this, the search for joint events from the independent experimental data of the Tunka-Grande and TAIGA-HiSCORE arrays carried out. The energy value was taken from the TAIGA-HiSCORE experimental data and the $\rho_{200}(0)$ parameter value - from the Tunka-Grande experimental data.



Energy Spectrum (3 operation seasons, ≈ 8080 h.)

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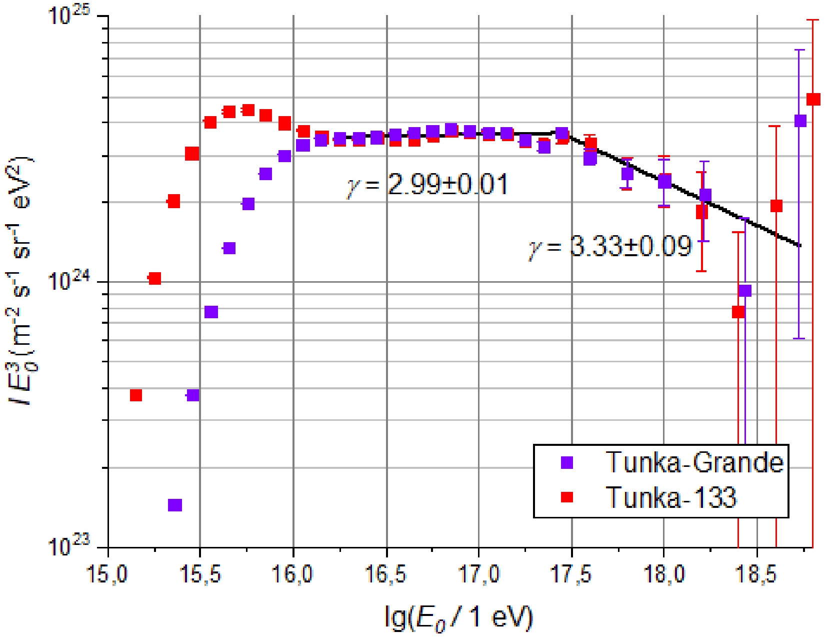
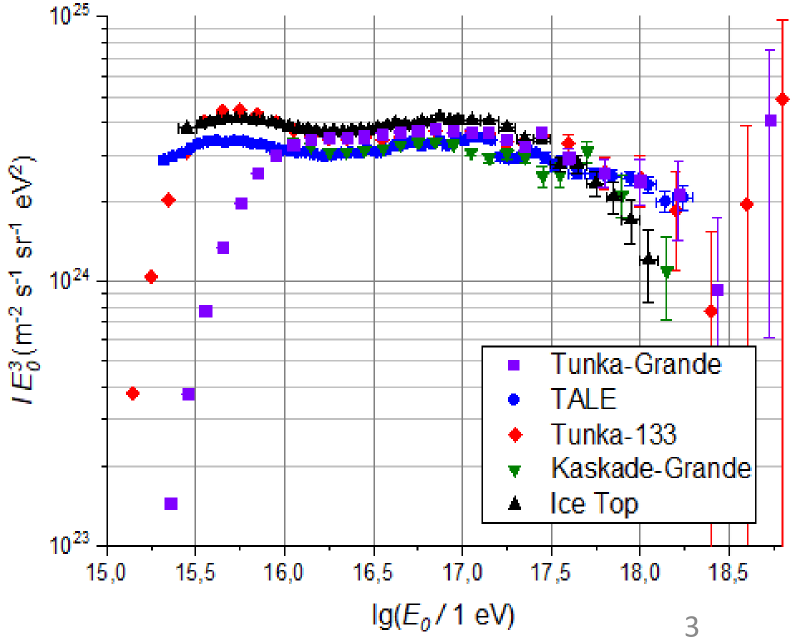
To plot the energy spectrum according to the results from processing the data collected by the Tunka-Grande facility, events with zenith angles $\theta \leq 45°$ and axial positions in a circle with radius $R < 400$ m were selected for energies $E_0 < 10^{17}$ eV, and in a circle with radius $R < 600$ m for showers with energies $E_0 \geq 10^{17}$ eV. A comparison of the spectra for the circle with radius $R < 400$ m and ring with inner radius $R > 400$ m and outer radius $R < 600$ m showed them to coincide within the limits of error, starting with the energy 10^{17} eV and up. The events with energy $E_0 > 10^{17}$ eV detected in the ring were naturally 1.25 times more numerous than in the circle. The efficiency of event selection was approximately 100% for energies $E_0 > 20$ PeV. The total number of events with energies higher than this was around 350000. Some 8070 events had energies over 10^{17} eV. The combined differential energy spectrum, reconstructed based on these results, for events with $R < 400$ m for $E_0 < 10^{17}$ eV and with $R < 600$ m for higher energies, is presented in Fig. 2. From energy of about 20 PeV to 300 PeV, the spectrum can be fitted by power-law with index $\gamma = 2.99 \pm 0.01$. At high energies, the power-law index grows abruptly to $\gamma = 3.33 \pm 0.09$ (a second knee). The spectrum is compared to results from Tunka-133 Cherenkov array. The spectra of both experiments are practically indistinguishable at the energy range $2 \cdot 10^{16}$–$5 \cdot 10^{18}$ eV.



The spectrum of this work in the range of 20 PeV–1EeV coincides with those collected by the KASCADE-Grande [3], TALE [4] and IceTop [5] facilities. The spectra reproduce the same structures. The difference between these spectra and one, acquired at the Tunka-Grande array, in the range of 20 – 100 PeV can be eliminated by raising the KASCADE-Grande and TALE energy estimate by 3% and reducing the IceTop estimate by the same amount. These changes are much lower than the absolute accuracy of the experiments.



Estimating the accuracy of the main EAS parameters experimentally

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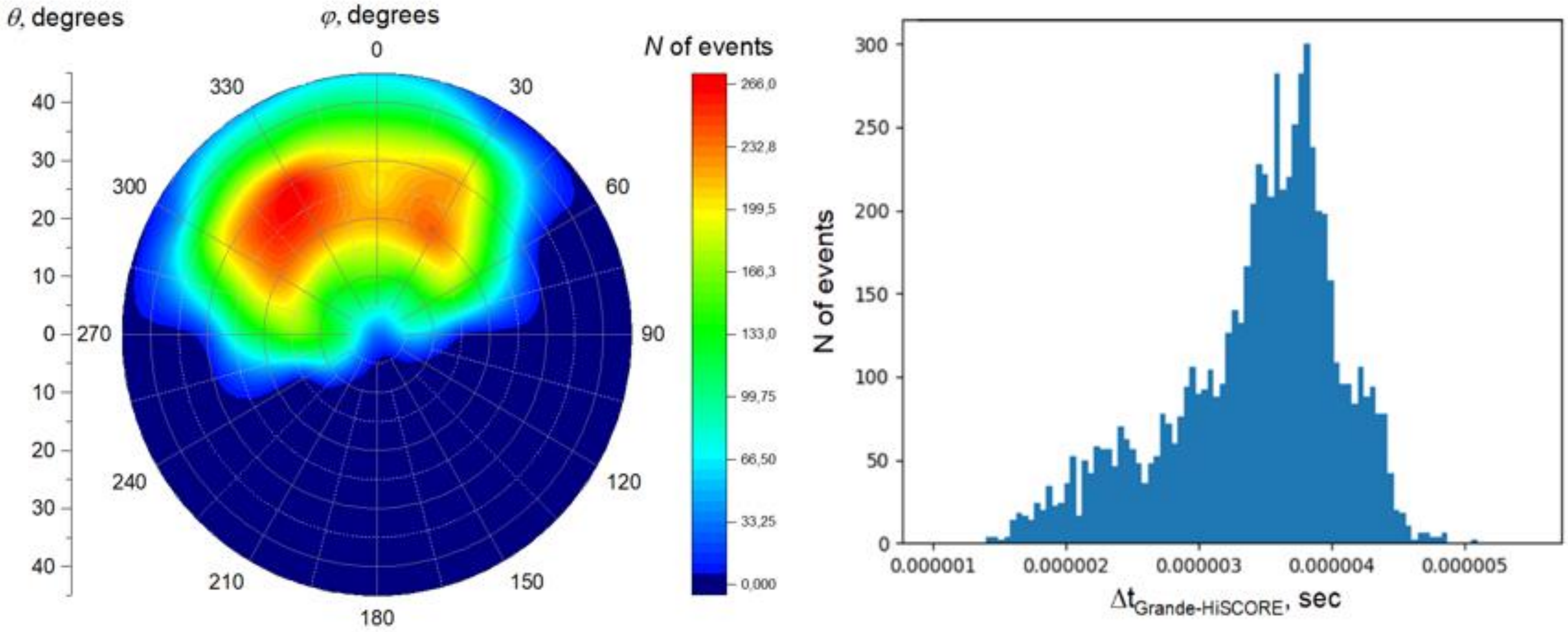
The **TAIGA-HiSCORE** and **Tunka-133** Cherenkov arrays demonstrate good performance and high reliability of equipment. Therefore, to determine the accuracy of the EAS parameters reconstruction, the EAS parameters reconstructed from experimental data of both Cherenkov facilities are used.

The search for joint events was performed within the time range of minus plus 10 microseconds in showers, registered in a circle with $R < 400$ m.

The TAIGA-HiSCORE Cherenkov array energy threshold is 0.2 PeV, which is significantly lower than the energy threshold of Tunka-Grande array (20 PeV). But the search for joint events of the Tunka-Grande and TAIGA-HiSCORE arrays gave positive results in this energy range.



Tunka-Grande and TAIGA-HiSCORE joint events. Left: Angular joint events distribution. Right: time difference between joint events

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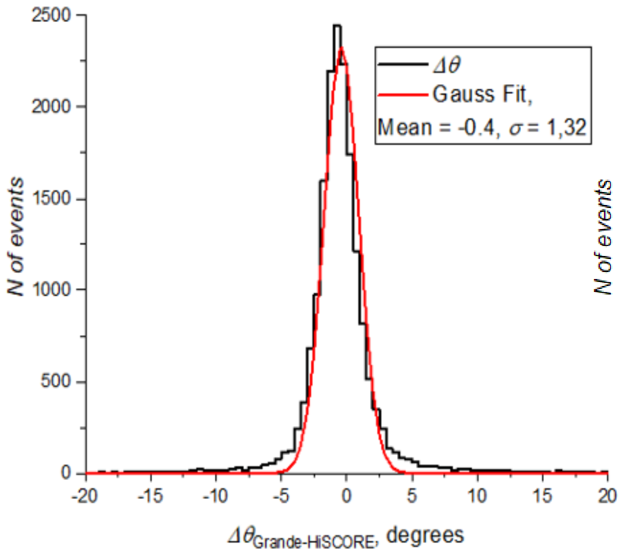
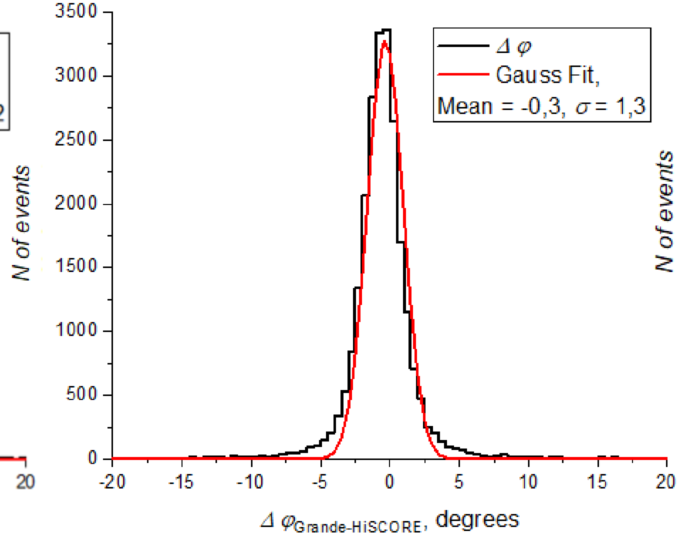
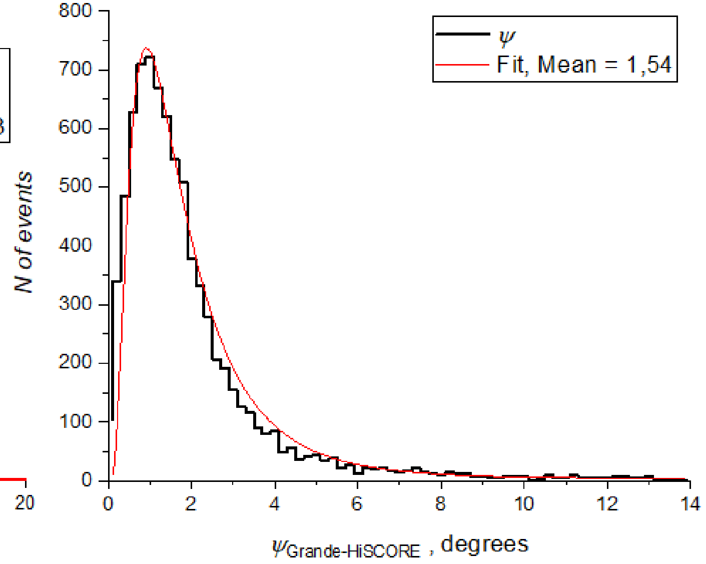




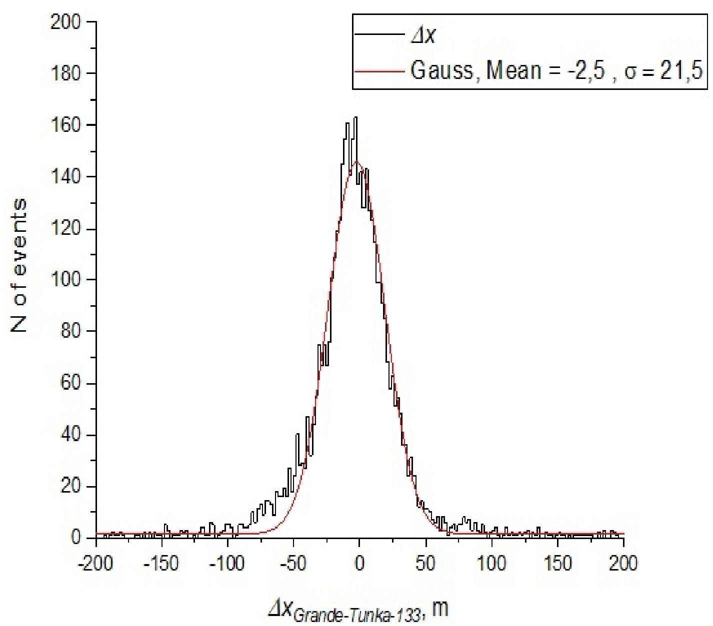


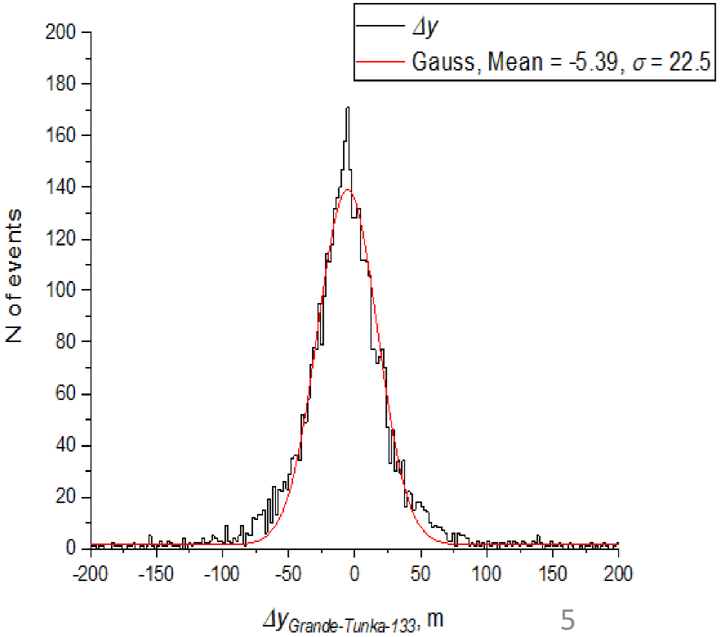
Figures on the left show the accuracy of the reconstruction of zenith and azimuth angles measured with the Tunka-Grande array in comparison with data of TAIGA-HiSCORE facility.

≈ 240 hours, 17300 joint events with 3 and more Tunka-Grande triggered stations

The comparison of Tunka-Grande and Tunka-133 experimental data was made by events detected by Tunka-Grande array under the Tunka-133 array trigger. This allowed us to estimate the scintillation array errors at the reconstruction of EAS core position, arrival direction, and energy for events with energies above 20 PeV.

Figures on the right show the accuracy of the reconstruction of shower core coordinates measured with the Tunka-Grande array in comparison with data of TAIGA-133 facility.





≈ 439 hours, 4500 joint events with 6 and more Tunka-Grande triggered stations

Estimating the accuracy of the main EAS parameters experimentally

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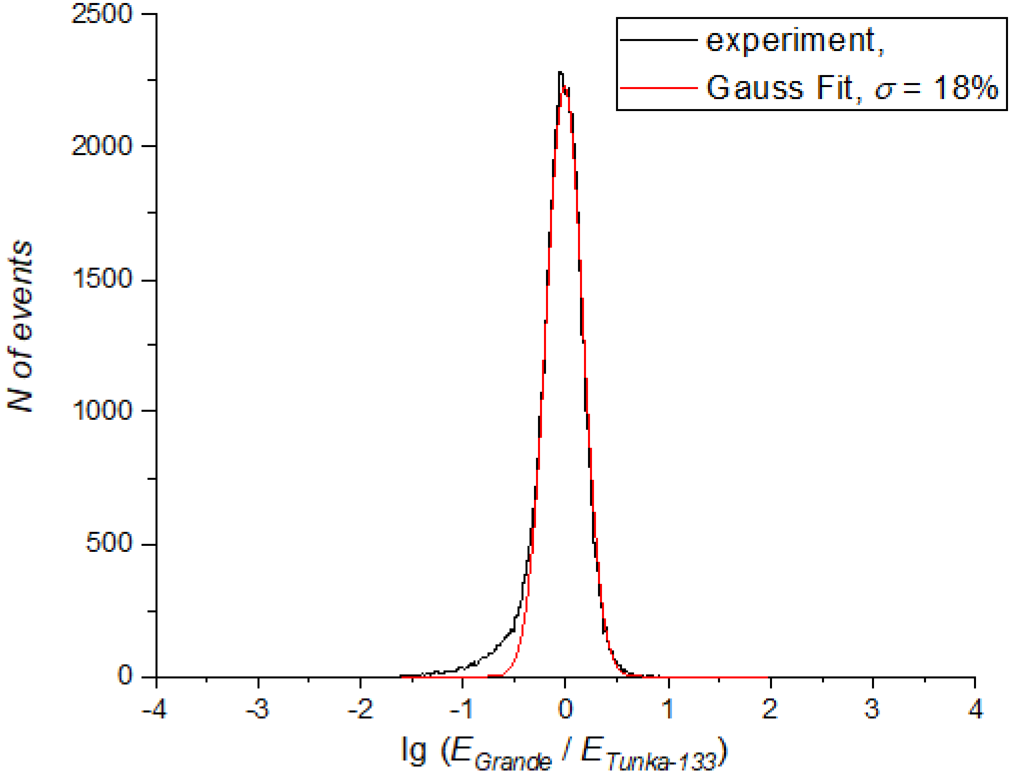
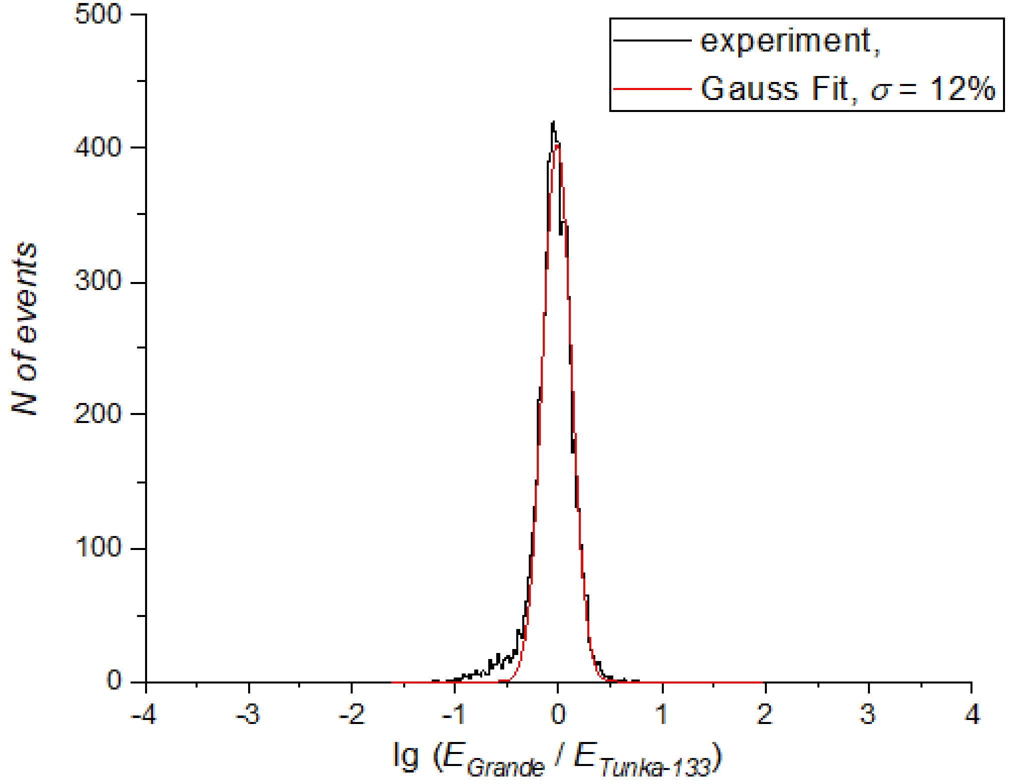
3 and more Tunka-Grande triggered stations, ≈ 53 000 events



6 and more Tunka-Grande triggered stations, ≈ 7500 events



The standard deviation of the ratio between the shower energies, reconstructed from the data of the Tunka-Grande and Tunka-133 arrays, is 18% for joint events with 3 and more Tunka-Grande triggered stations and 12% for joint events with 6 and more Tunka-Grande triggered stations.

Conclusion

- The primary cosmic-ray energy spectrum based on 3 Tunka-Grande operation seasons was reconstructed. The spectrum in the energy range of 2×10^{16}–10^{18} does not obey the unified power law but has a number of characteristic features: at the energy range 2×10^{16} - 3×10^{17} eV, the value of the power spectrum index is $\gamma = 2.99 \pm 0.01$. At higher energies, the spectral index rises sharply to $\gamma = 3.33 \pm 0.09$ (the second knee). In the energy range of 10^{16}–10^{17} eV, the agreement is observed between the results of this work and the spectra obtained by the Kaskade Grande[3], TALE[4] and Ice TOP[5] arrays.
- The search for joint events of the Tunka-Grande and TAIGA-HiSCORE arrays gave positive results. The presence of such events indicates the possibility of joint analysis of the data of the scintillation experiment and the Cherenkov facilities for the study of mass composition and gamma-hadron separation at energies below 10 PeV.

References

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