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# Scintillation experiment on the study of cosmic rays and gamma-quanta fluxes in the Tunka Valley

Novosibirsk State University

## The CR and EAS parameters reconstruction technique from the experimental data of the Tunka-Grande scintillation array

*A.Ivanova[1,2] for TAIGA Collaboration*

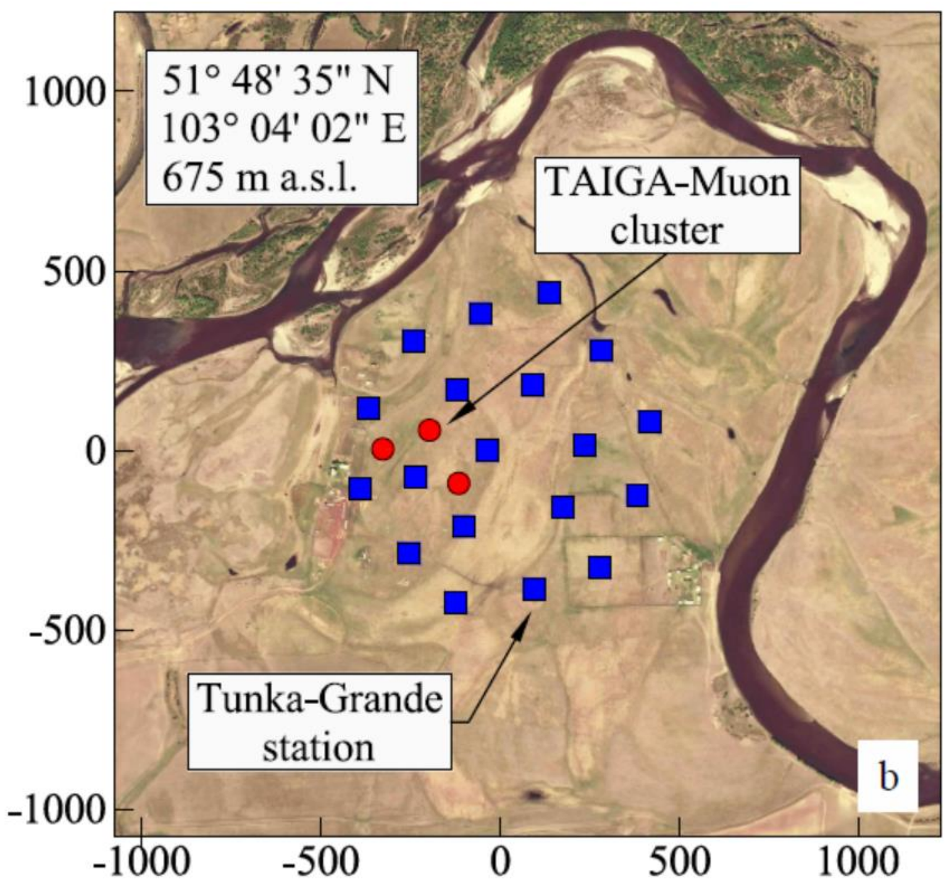
*1-Irkutsk State University, 664003, Irkutsk, Russia, 2-Novosibirsk State University, 630090, Novosibirsk, Russia*

Irkutsk State University

**Tunka-Grande Scintillation array:**

19 Scintillation Stations on area ≈ 0,5 km².
Scintillation Station = Surface detector + Underground detector ;
Surface detector =12 scintillation counters;
Underground detector = 8 scintillation counters.

- Scintillation counter area – 0.64 m².
- Surface detector area ~ 8 m².
- Underground detector area ~ 5 m².
- Distance between stations ~ 175 m.
- Altitude of 669 m a.s.l.




**TAIGA-Muon Scintillation array:**

The TAIGA-Muon detectors complement the existing Tunka-Grande scintillation array.
Currently, the TAIGA-Muon array is under construction. The first 3 TAIGA-Muon clusters have been deployed and put into operation. The estimated total area of the TAIGA-Muon array is about 2000 m2.
**Each Cluster:** 8 surface and 8 underground detectors are combined in pairs (the surface ones are strictly above the underground ones) and are located along the periphery of a square with a side of 5m.

**The main aim of the scintillation experiment is a detailed study of the energy spectrum and mass composition of cosmic rays and search for astrophysical gamma-rays in the energy range from 100 TeV to 1 EeV by detecting the charged and muon component of EAS.**

## Reconstruction technique of the Tunka-Grande experimental data

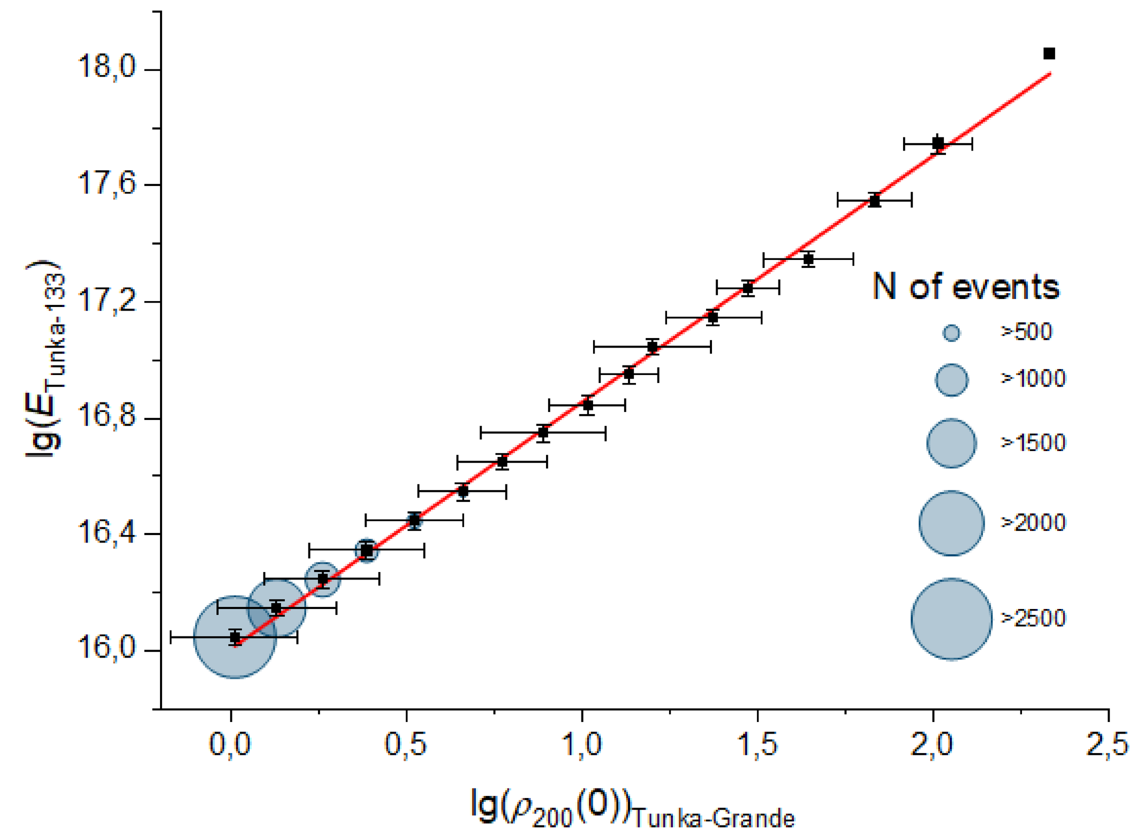
- Detector signal converted to charged particle density using most probably energy deposit per charged particle.
- The shower arrival direction, parametrized by the shower axis's zenith and azimuth angles, is determined by fitting the measured pulse front delay using a curved shower front formula, which is obtained in a KASCADE-Grande experiment [1]: $T_i - T_{th} = a(1 + R_i/30)^b$.
- The lateral distribution of charged particles is described using the specific EAS-MSU function[2]:
- The lateral distribution of muons is described using the Greisen function [3].
- The shower core coordinates, number of muons and charged particles, and slope of the LDF are calculated in minimizing the functional using independent variables.
- As a measure of energy, we use the charged particles density at a core distance of 200 meters – ρ200.
- The $\rho$200 parameter is rescaled relative to the measured zenith angle as:
- $\rho_{200}\,(0) = \rho_{200}\,(\theta) \cdot \exp(\frac{x_0}{\lambda} \cdot (sec\theta - 1))$

there $x_0$ = 960 g/sm² is the atmospheric depth from sea level for the Tunka Valley,
λ = 260 g/ sm² – obtained from experimental data average value of absorption path length.

- The value of $\rho_{200}(0)$ relative to the energy can be rescaled as:

$E_0 = 10^b \cdot \left(\rho_{200}(0)\right)^a$, where $a$ = 0.84, $b$ = 15.99 - the average values of the coefficients (depending on the conditions, imposed on the selection of joint events, $a$ varies within 5%).

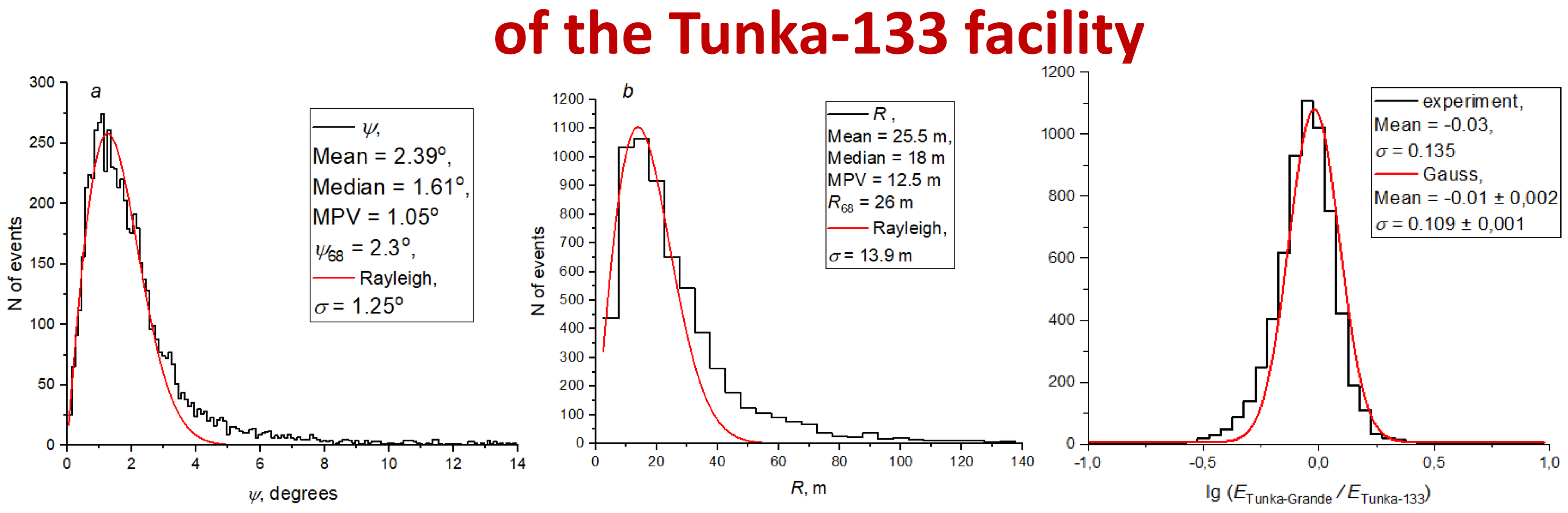
- Correlation $\rho_{200}(0)$ with the primary energy is determined using the experimental results of Tunka-133 Cherenkov array.




[1] Glasstetter R *et al* 2005 *29th International Cosmic Ray Conference Pune* **6** 293-296
[2] Fomin Yu A *et al* 1996 *J. Phys. G: Nucl. Part. Phys.* **22** 1839-1849
[3] Monkhoev R D *et al* 2017 *Bull. Russ. Acad. Sci.* **81** 4 468-470

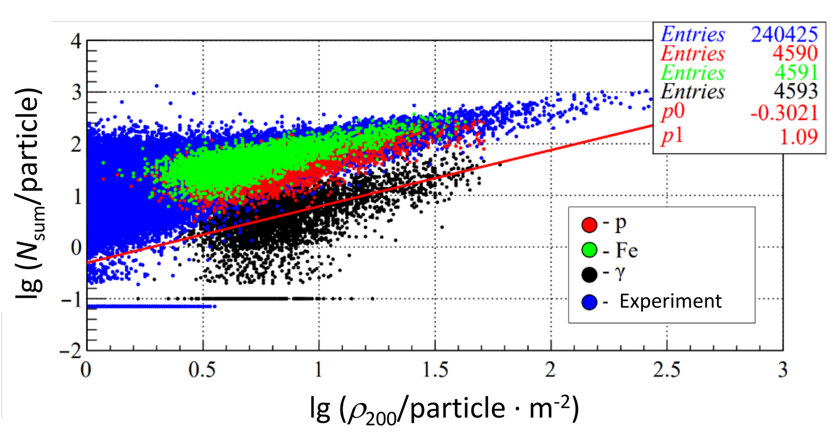
**This technique is based on a comparison of experimental data and practically does not depend on the hadron interaction model.**

## Accuracy of the EAS and CR parameters reconstruction by the Tunka-Grande array in comparison with the results of the Tunka-133 facility

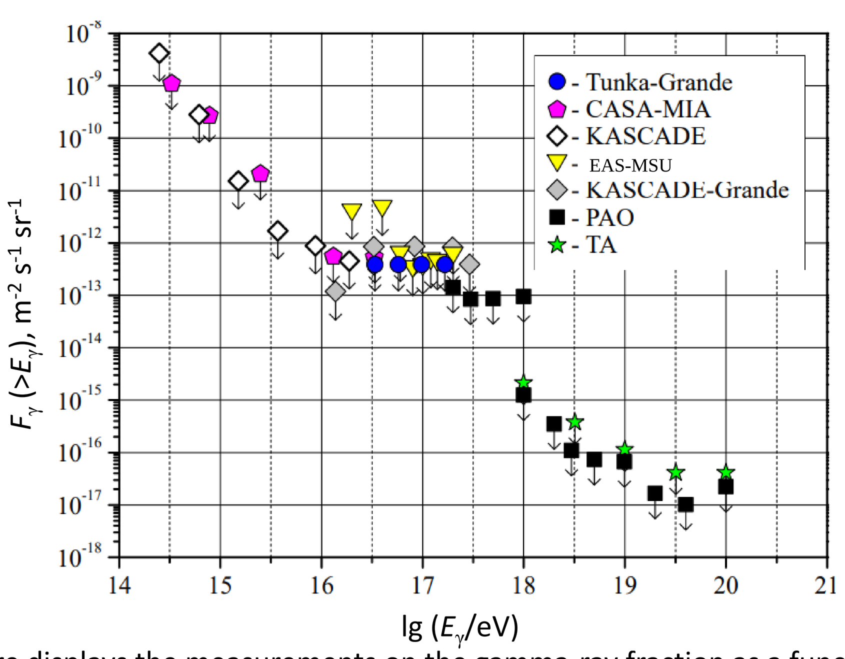



Tunka-Grande Angular resolution = Confidence Level 68% ≤ 2,3°.
Tunka-Grande Core Position Resolution = Confidence Level 68% ≤ 26 m.
The Energy Resolution for the described reconstruction technique, equal to the standard deviation of this histogram is 36%.

## Gamma-hadron discrimination



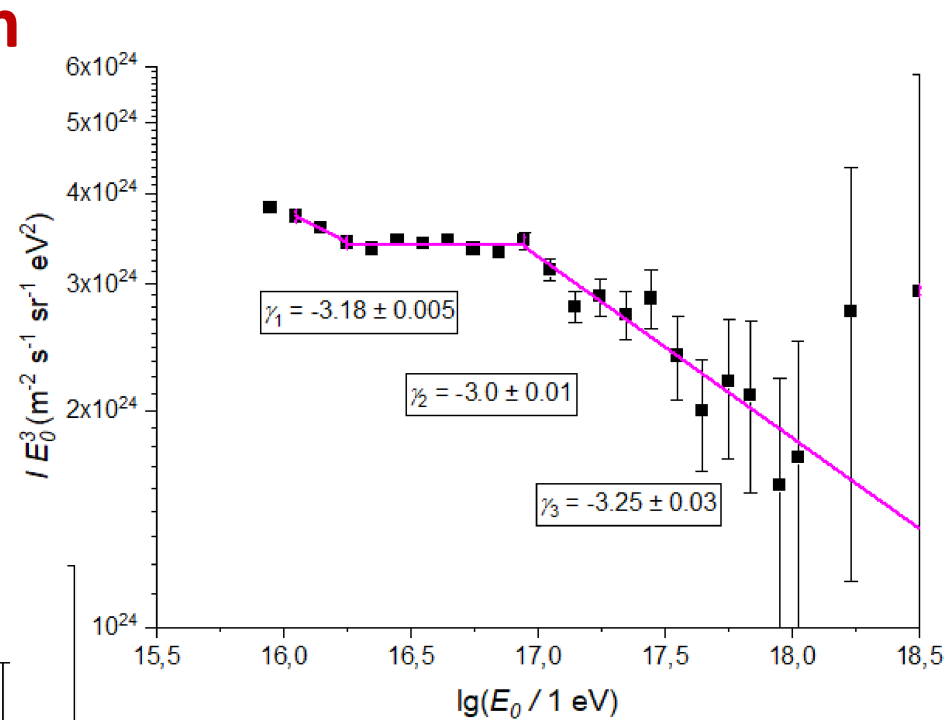

The Figure a shows the distribution of the muon number in underground Tunka-Grande detectors versus ρ200 parameter for measured showers by Tunka-Grande with simulated showers. Lower red line indicates the selection criteria. There is no events consistent with a gamma-ray signal seen in the data. Hence, we set upper limits on the gamma-ray fraction of the cosmic rays.

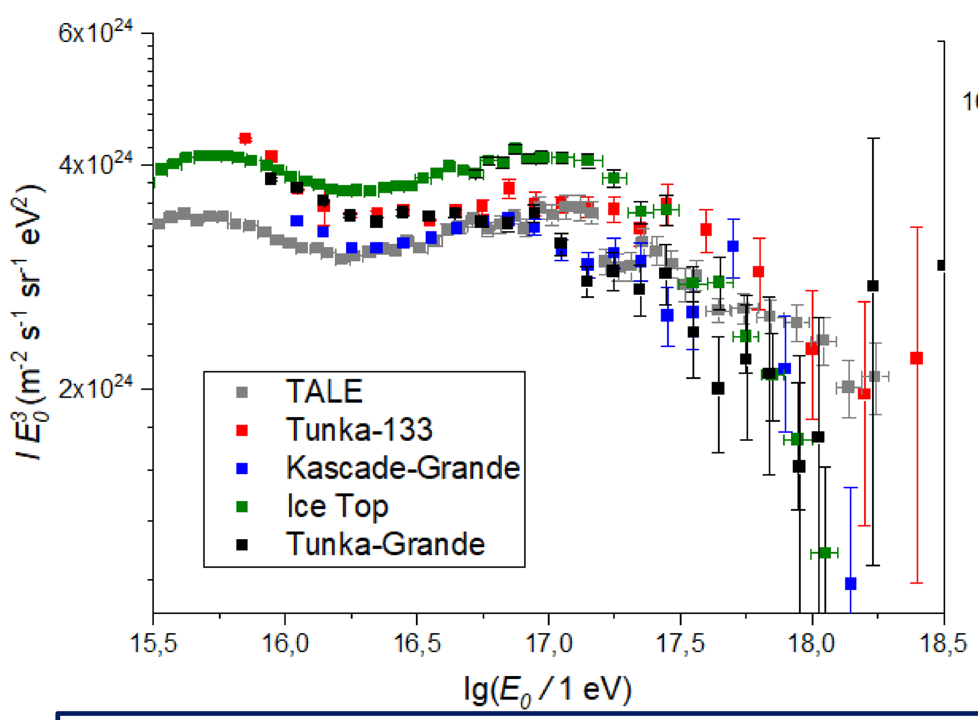



The Figure displays the measurements on the gamma-ray fraction as a function of the energy, including this work, for the energy range of 10 PeV up to 100 EeV. Tunka-Grande - 90% C.L., QGSJET-II-04, EAS-MSU - 90% C.L., QGSJET-II-04, KASCADE-Grande - 90% C.L., QGSJET-II-02, Pierre Auger Observatory - 95% C.L., EPOS LHS, Telescope Array - 95% C.L., QGSJET-II-03.

## All particle energy spectrum

- Statistics - 4 observation seasons;
- zenith angle ≤ 35° and core position in circle with R ≤ 350 m;
- $E_{threshold}$(100% registration efficiency) = 10 PeV (from simulation)
- ~ 240000 events with energy $E \geq$ 10 PeV;
- ~ 2000 events with energy $E \geq$ 100 PeV;




Comparison of energy spectra obtained at Tunka-Grande with some other experimental results (TALE [1], Tunka-133[2], Kascade-Grande [3], Ice Top [4])

[1] Abbasi R. U. *et al,* 2018, *Astrophysical journal* **865** 74,
[2] Prosin V. V. *et al,* 2020, *Astroparticle physics* **117** 102406
[3] Apel W. D. *et al,* 2012, *Astropart. Phys.* **36** 183,
[4] Rawlins K. *et al,* 2016, *J. Phys. Conf. Ser.* **718** 5 052033

### Conclusion

➢ Comparison of the Tunka-Grande array data with the data of the Tunka-133 Cherenkov facility confirmed the sufficient quality of the reconstructed events for their further use in joint analysis for primary composition and gamma-hadron separation:

- angular resolution ≤ 2.3°;
- core position resolution ≤ 26 m;
- Energy resolution ≤ 36%.

➢ Based on 4 measurement seasons All-particle energy spectrum was reconstructed and the 90% C.L. upper limits to the diffuse flux of ultrahigh energy gamma rays for energies above 10 PeV were determined.

PRELIMINARY