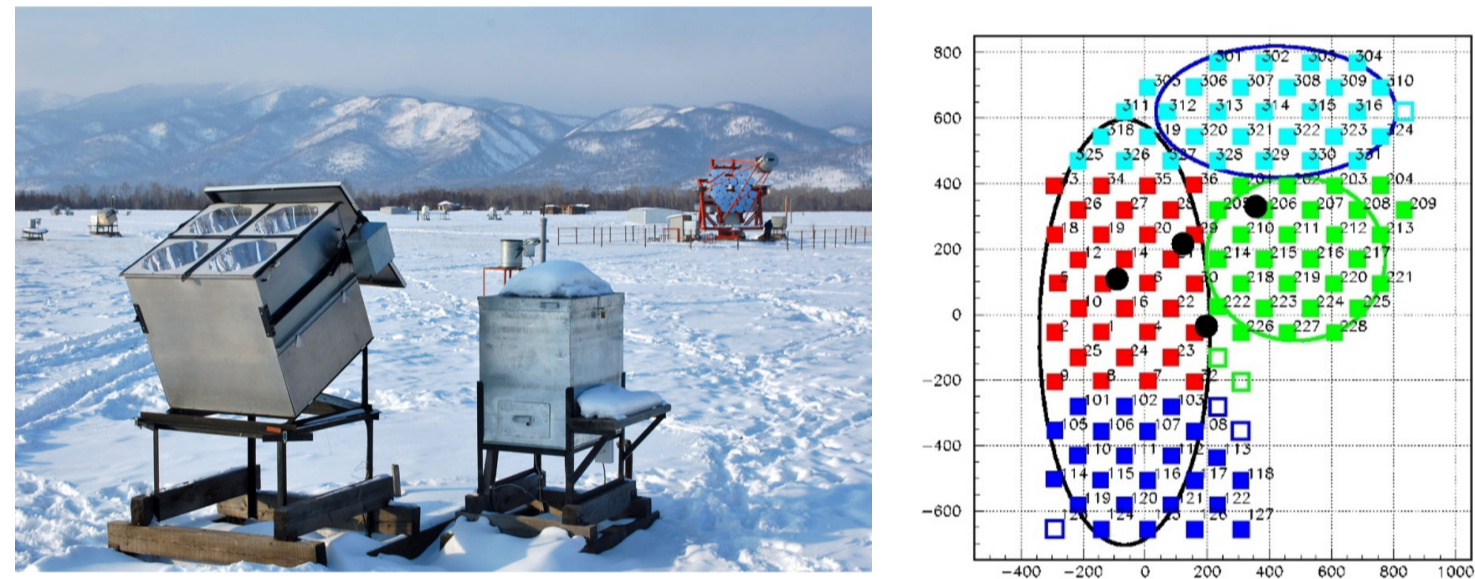


Energy spectrum and mass composition of cosmic rays according to the data of the TAIGA-HiSCORE installation

N. Budnev, L. Kuzmichev, E. Osipova, V. Prosin, M. Ternovoy for TAIGA collaboration

Since 2022, the TAIGA-HiSCORE installation as part of the TAIGA astrophysical complex has been operating as part of 120 Cherenkov stations on an area of 1 km², the energy of the EAS was determined by the flux density of Cherenkov light at a distance of 200 m from the EAS for energies above 1 PeV and by the flux density at a distance of 100 m from the axis of the EAS for lower energies. The depth of the EAS maximum was determined by the steepness of the spatial distribution function of light, which was the ratio of light fluxes at distances of 80 and 200 m from the axis. The energy spectrum and mass composition of cosmic rays obtained over 700 hours of data collection are presented.

Current Status of the TAIGA-HiSCORE



- The wide-angle Cherenkov array covers an area of up to 1 km² with 120 stations in zenith (2022-2023 season, autumn 2023) or inclined orientation (2021-2022, 2023-2025);
- In full configuration with 4 clusters – from 2021 to the present;
- Each station is equipped with a set of four large photomultiplier tubes (PMTs). The time resolution of each station is 10 ns. Time step is 0.5 ns.

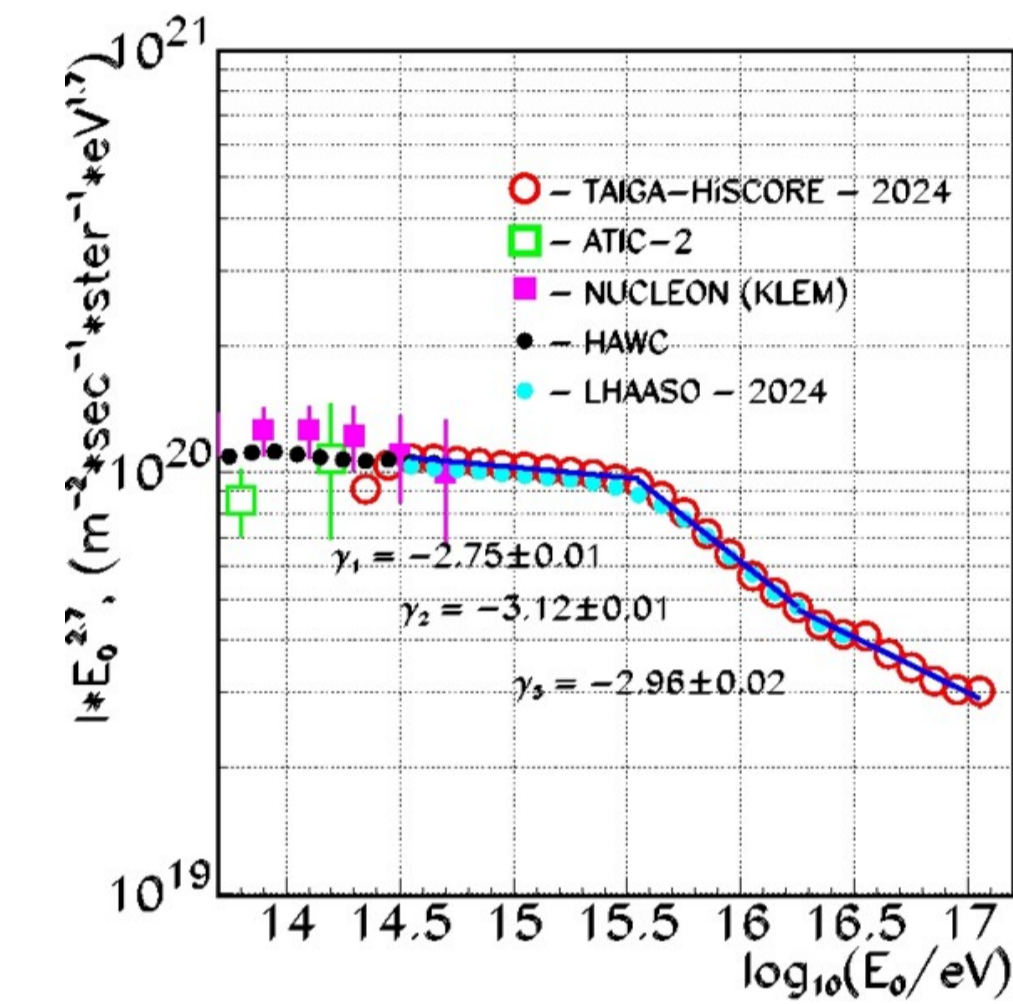
Simulation for method

To analyze the possibility of determining the shower maximum depth using method applied at HiSCORE, simulations were conducted with the following parameters:

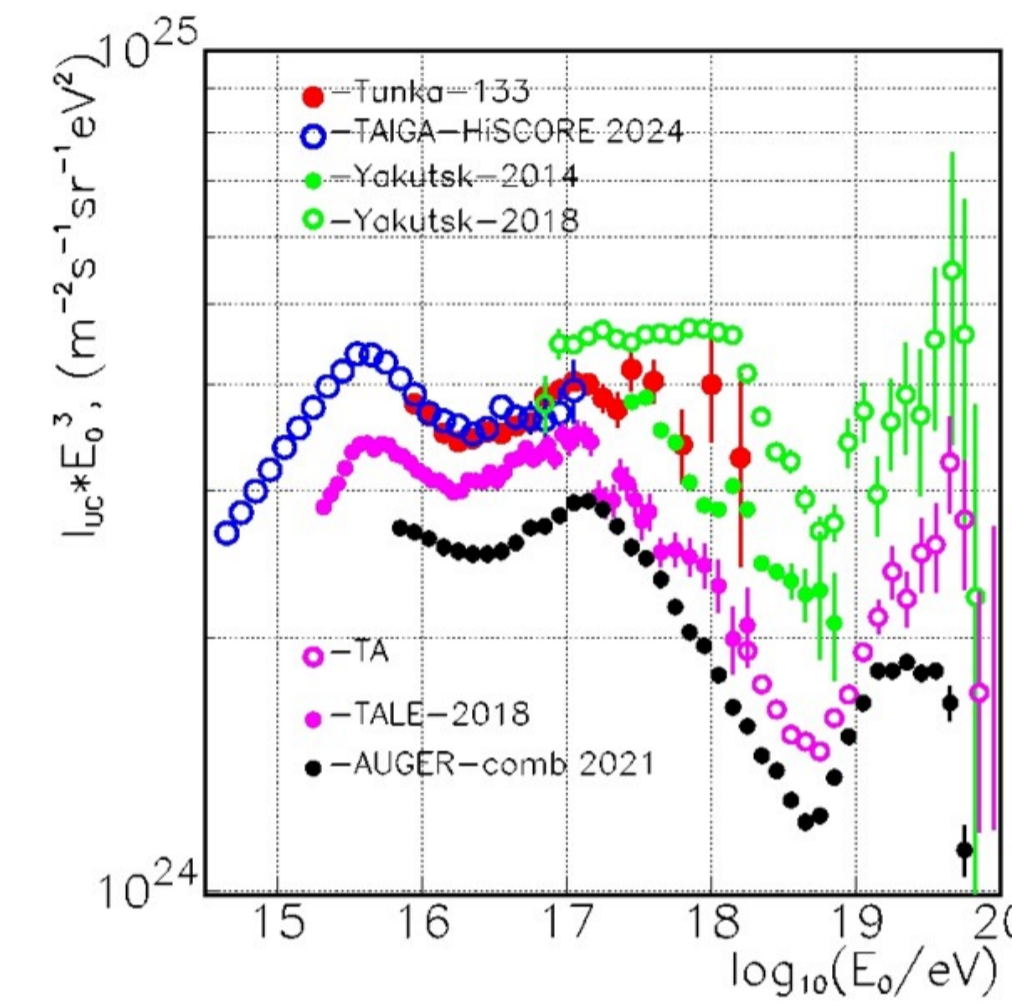
- CORSIKA¹+(QGSJet-II-04² or Sybill2.3d³);
- Primary energy: 1,3,10,30,100 PeV;
- Angles: 0, 30°;
- Primary particles: proton, helium, iron;
- No statistical thinning;
- The Cherenkov light simulation option was also used (bunch=1 photon), which significantly increased the computational time per shower (by 15-20 times).

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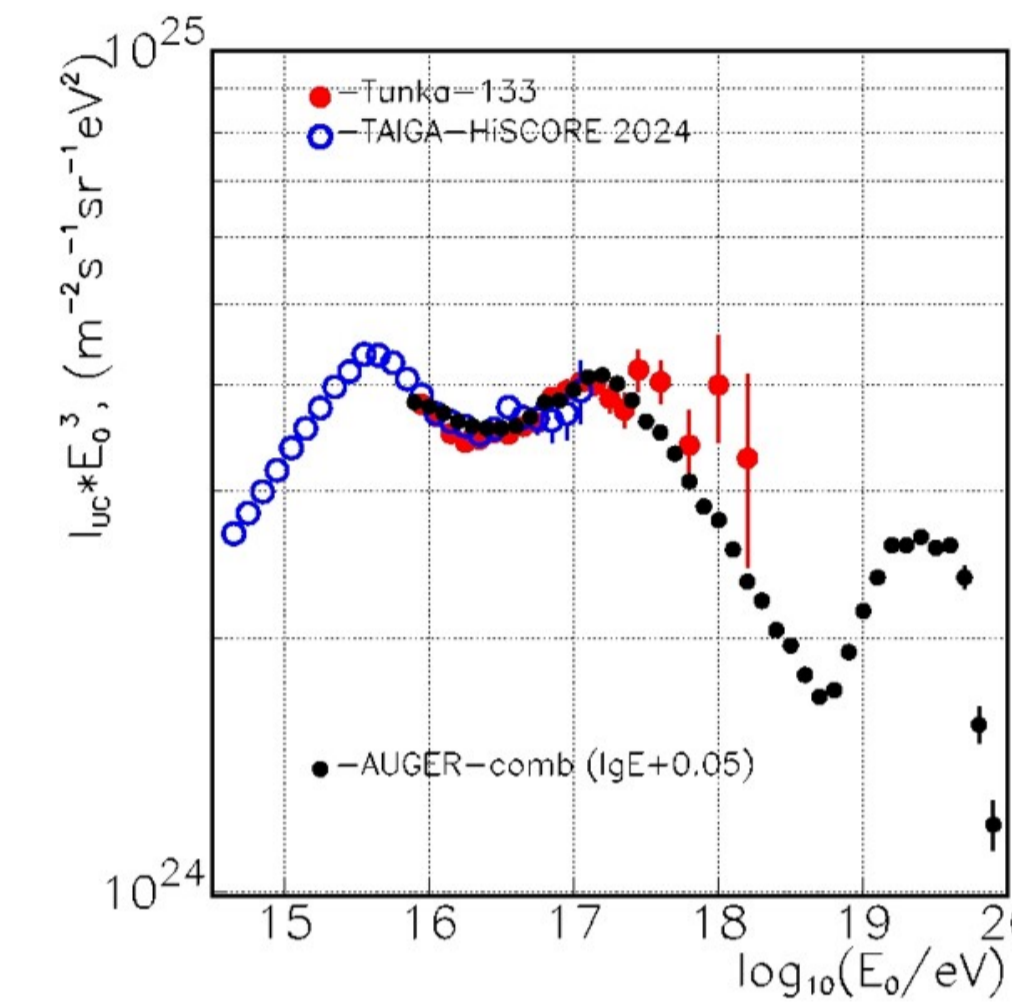
Experimental energy spectrum for the 3 seasons of observation 2021 – 2024



Statistics: 167 nights, 705 hours. Effective area 1.03 km²
 Combined spectrum using the solid angles as the weights



Comparison with the Giant Arrays^{4,5,6,7,8,9} results: the giant arrays claim two main features of the spectra: the second knee and the ankle, but they have a little bit different energy calibration



Separate comparison with PAO (combined), shifted by energy to 12%

- All particles energy spectrum in the range 300 TeV – 3 PeV has no any special features – changes of the power law index 2.75 ± 0.01 . The classic knee at 3 PeV is well confirmed. The first ankle at about 20 PeV is confirmed too;
- Our pure Cherenkov light spectrum agree with the spectra of direct satellite and balloon experiment^{10,11} as well as the high mounting experiments HAWC¹² and LHAASO¹³;
- We plan to enlarge the energy range of TAIGA-HiSCORE measurements with the additional low gain detectors and continue analysis of the Tunka-133 array data to reach the proof of the second knee.

New P vs ΔX_{max} dependence

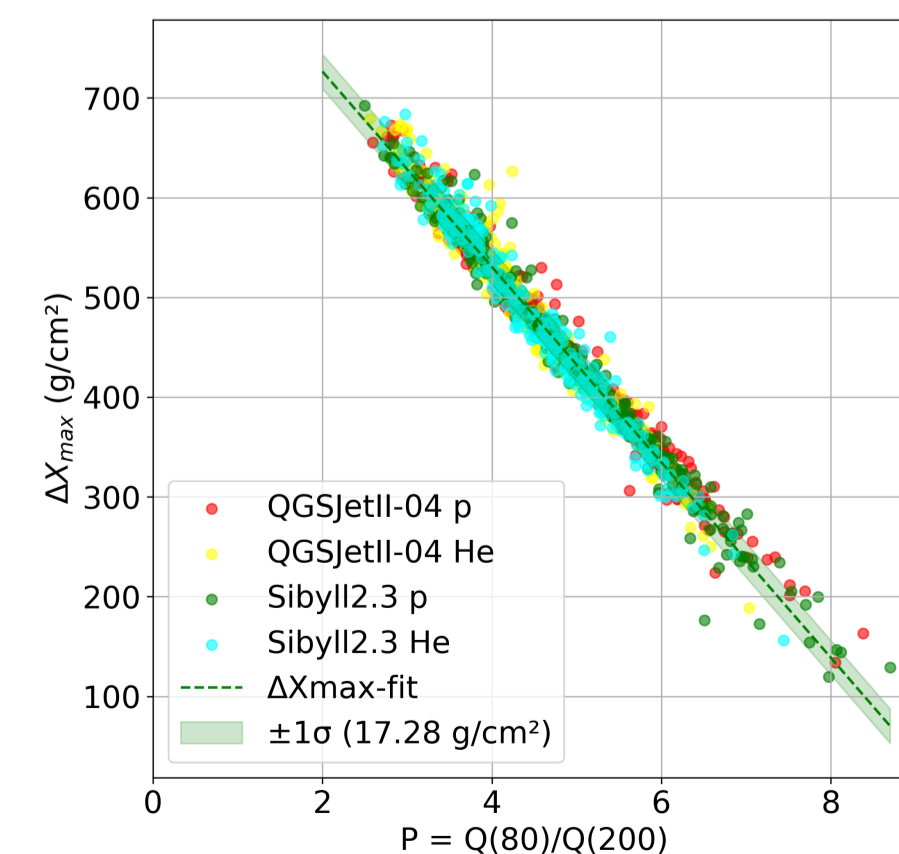
The shower maximum depth is determined using the ratio of light flux at distances of 80 and 200 m from the axis.

Steepness: $P = Q(80)/Q(200)$
 (parameter introduced in 2021);
 Relative position of the maximum: $\Delta X_{max} = X_0/\cos\theta - X_{max}$
 where $X_0 = 965 \text{ g/cm}^2$ (relative to the observation array);

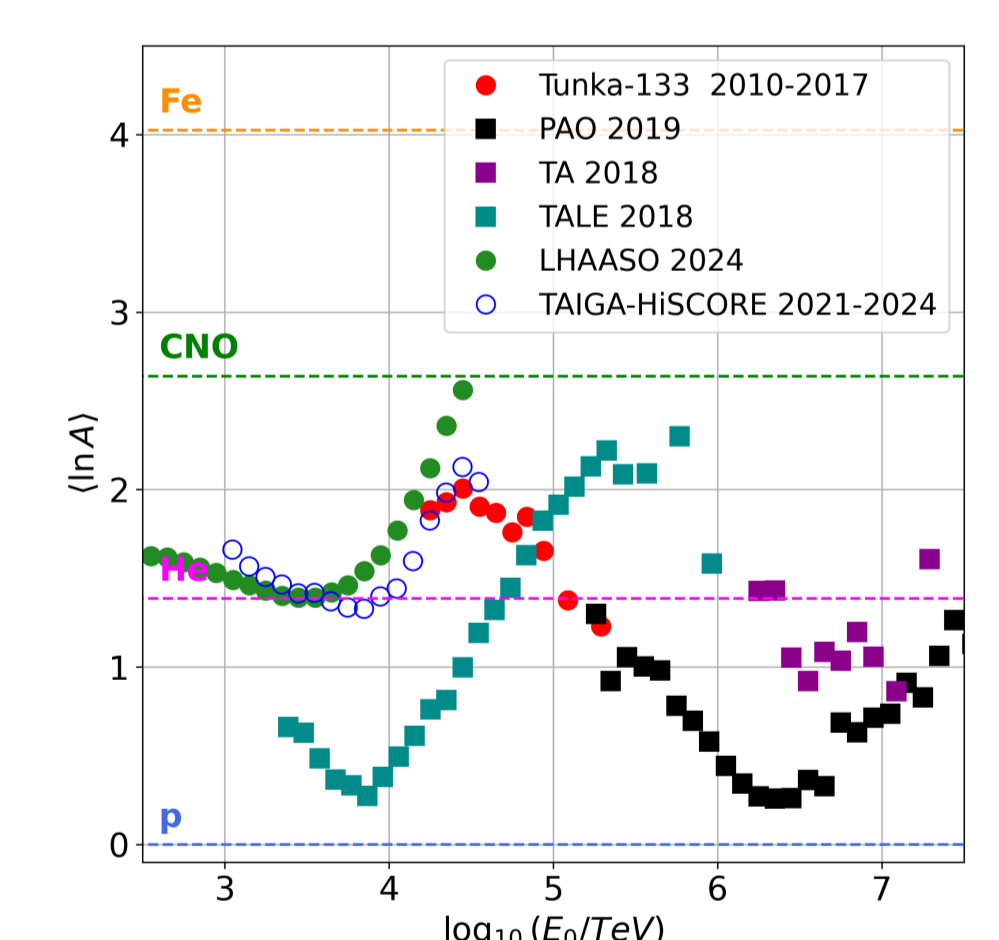
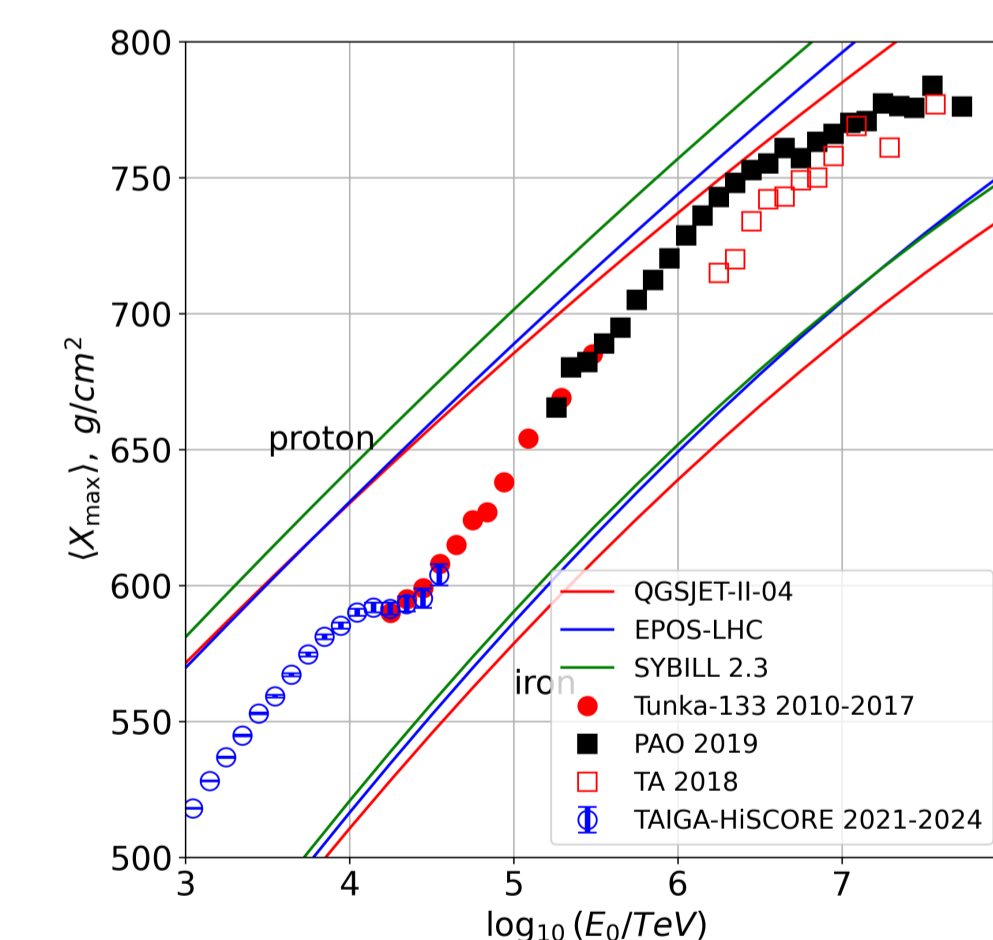
The experimental steepness distribution is within the sensitivity of P to ΔX_{max} under the given constraints on zenith angle and energy. The transformation from parameter P to ΔX_{max} is independent of:

- Energy ($10^{15} - 10^{17} \text{ eV}$),
- Zenith angle of the shower ($0^\circ - 30^\circ$),
- Hadron interaction model.

$$\Delta X_{max} = -98 \cdot P + 922, \sigma = \pm 17.28 \text{ g/cm}^2$$



$\langle X_{max} \rangle$ and $\langle \ln A \rangle$ estimation for the 3 seasons of observation 2021 – 2024



- For TAIGA-HiSCORE statistics: 2021-2024 seasons, 905283 events <30 PeV, 4 clusters, zenith angles $\theta \leq 30^\circ$, effective area 1 km²;

- Direct dependence $\langle \ln A \rangle \sim \langle X_{max} \rangle$ by linear interpolation:

$$\langle \ln A \rangle = \frac{X_{max}^p - X_{max}^{data}}{X_{max}^p - X_{max}^{Fe}} \cdot \ln 56$$

- The QGSJet-II-04 model was used to recalculate $\langle \ln A \rangle$;

- For comparison, data from the LHAASO¹³, Pierre Auger Observatory⁷, Telescope Array⁸, TALE⁹ and Tunka-133⁴ experiments were used;

- Across the entire energy range, a slightly lighter composition (p + He) is observed, confirming the heavier composition of cosmic rays in the $3 \cdot 10^{15} - 3 \cdot 10^{16} \text{ eV}$ range and its lighter composition at energies above $3 \cdot 10^{16} \text{ eV}$.