TAIGA

IRKUTSK STATE UNIVERSITY

EAS Maximum Depth from the Space-Time Structure of Cherenkov Light Based on the TAIGA-HiSCORE Data

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Methods for Measuring EAS Maximum Depth

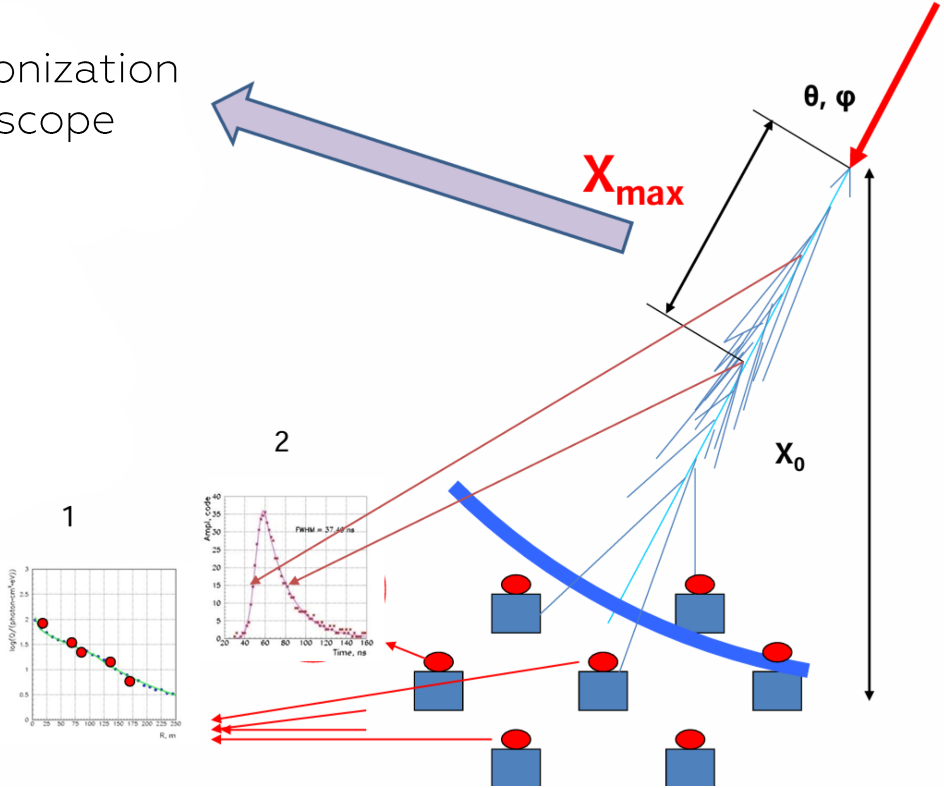
- **10^{18} - 10^{20} eV**

Direct observation of X_{max} through ionization light, as in the Pierre Auger and Telescope Array experiments.

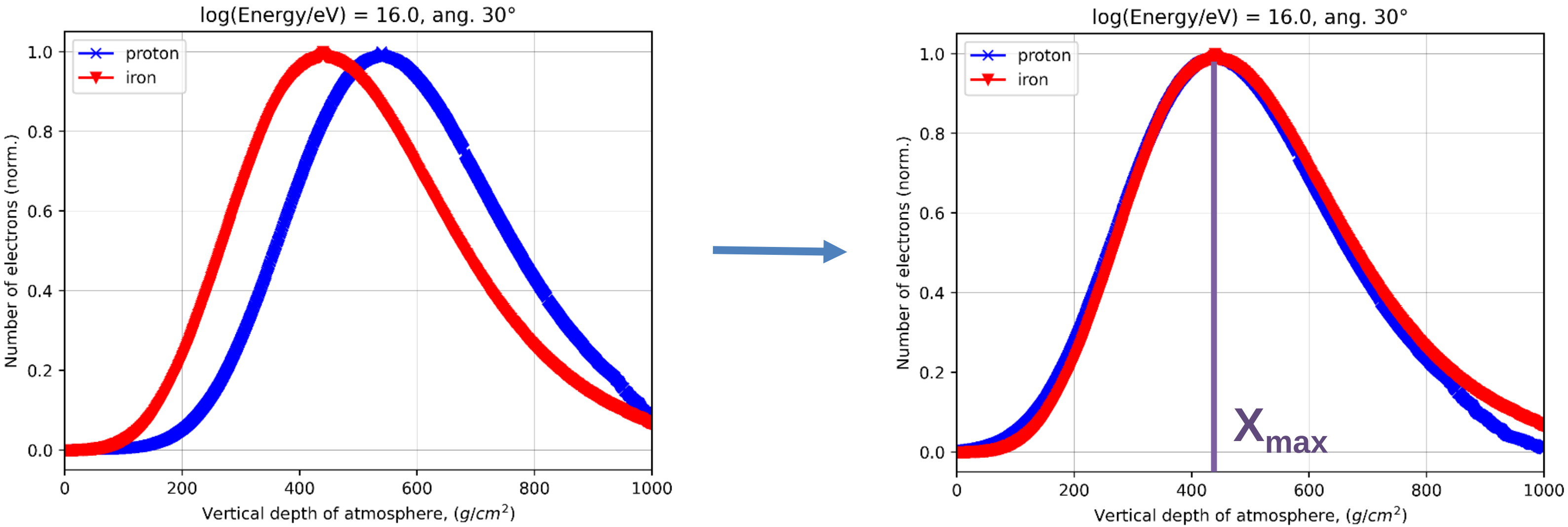
- **10^{15} - 10^{18} eV**

Two methods for estimating X_{max}:

- Steepness of the spatial light distribution function (LDF): **P** = $Q(R_1)/Q(R_2)$, $R_2 > R_1$ **(P-method).**
- Pulse width at half-height (FWHM), **$\tau_{1/2}$ (τ-method).**



Similarity of Cascade Curves



- Cascade curves describe the electron density in a shower as a function of atmospheric depth;
- The shapes of cascade curves, which determine the electron density in a shower as a function of atmospheric depth, are nearly identical for different types of primary particles. CORSIKA simulations confirm this fact;
- **Therefore, the shower maximum depth X_{max} can be considered the primary parameter for assessing the mass composition**.

X_{max} Dependence on Primary Composition

- **The difference between primary compositions at 10 PeV (lg (E/TeV) = 4) can be divided into approximately 4 equal parts:**
  - Proton – 630 g/cm²;
  - Helium – 590 g/cm²;
  - Nitrogen – 550 g/cm²;
  - Iron – 510 g/cm².

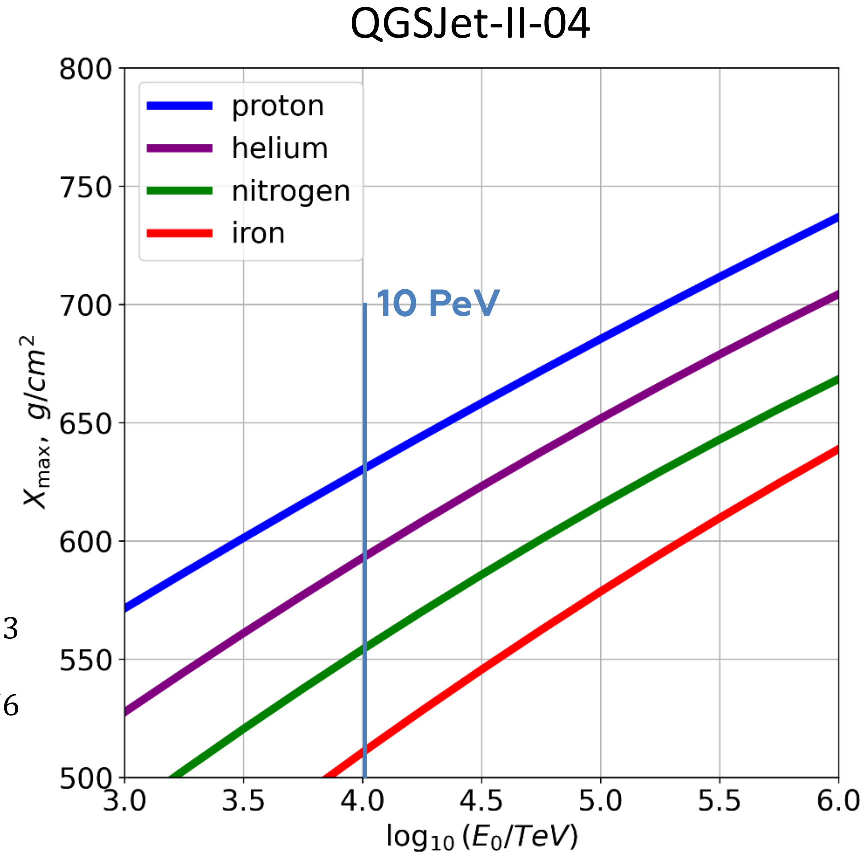
The difference between proton and iron compositions is ~120 g/cm²;

Proton

$$X_{max} = -1.798 \cdot \log E/TeV^2 - 71.355 \cdot \log E/TeV + 373.53$$

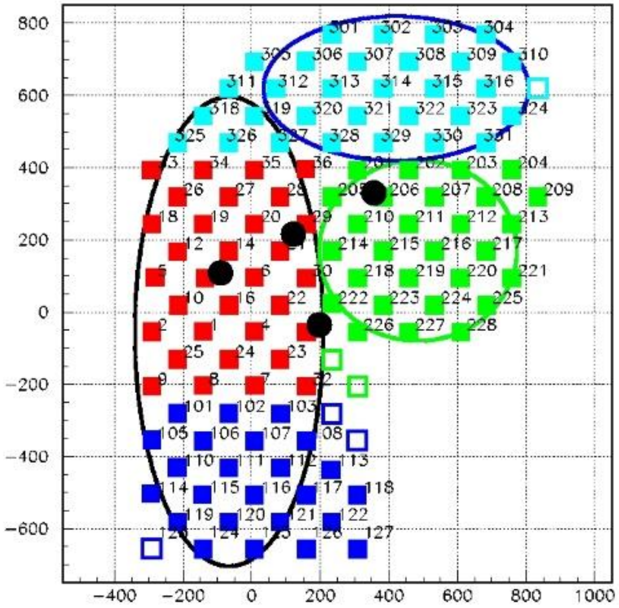
Iron

$$X_{max} = -3.888 \cdot \log E/TeV^2 - 103.00 \cdot \log E/TeV + 160.76$$



Current Status of the TAIGA-HiSCORE Array

- The array covers an area of up to 1 km² with 114 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.**



Simulations for X_{max} Determination Methods

- To analyze the possibility of determining the shower maximum depth using methods applied at HiSCORE, simulations were conducted with the following parameters:
  - **CORSIKA**+(**QGSJet-II-04** or **Sybill2.3d**) + **GHEISHA2002d**;
  - 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 ph), which significantly increased the computational time per shower (by 15-20 times).**

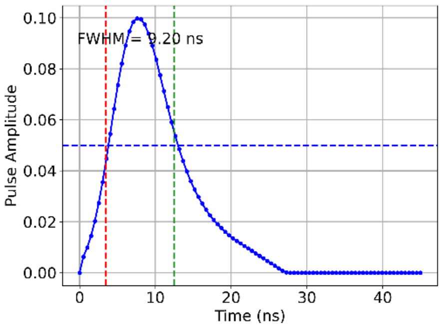
Pulse Width (FWHM) Measurement at HiSCORE

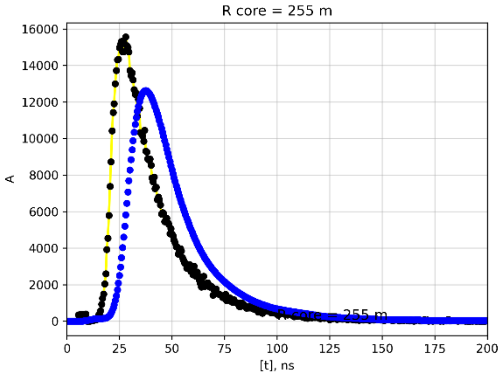
- To estimate pulse duration in the experiment, signals from the anode channels of PMTs are used. The general data processing algorithm includes several stages:

    - Signals are time-shifted by 0.5 nanoseconds to improve measurement accuracy;
    - Signals from four PMTs at a single station are summed to obtain the resulting pulse;
    - After summation, the resulting pulses are convolved with the station's instrumental function.

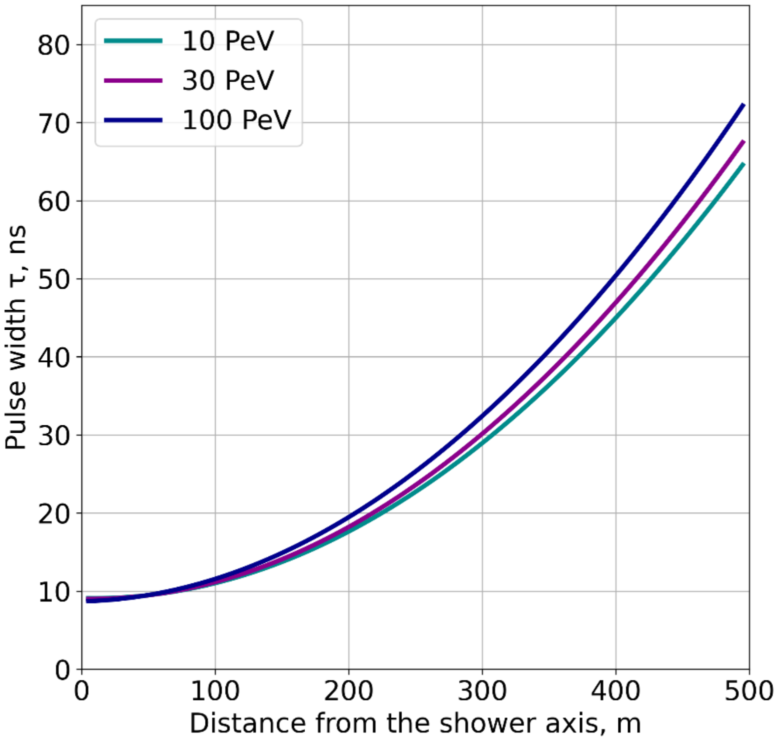
    The instrumental function is characterized by a duration of about 10 nanoseconds for anode channels.

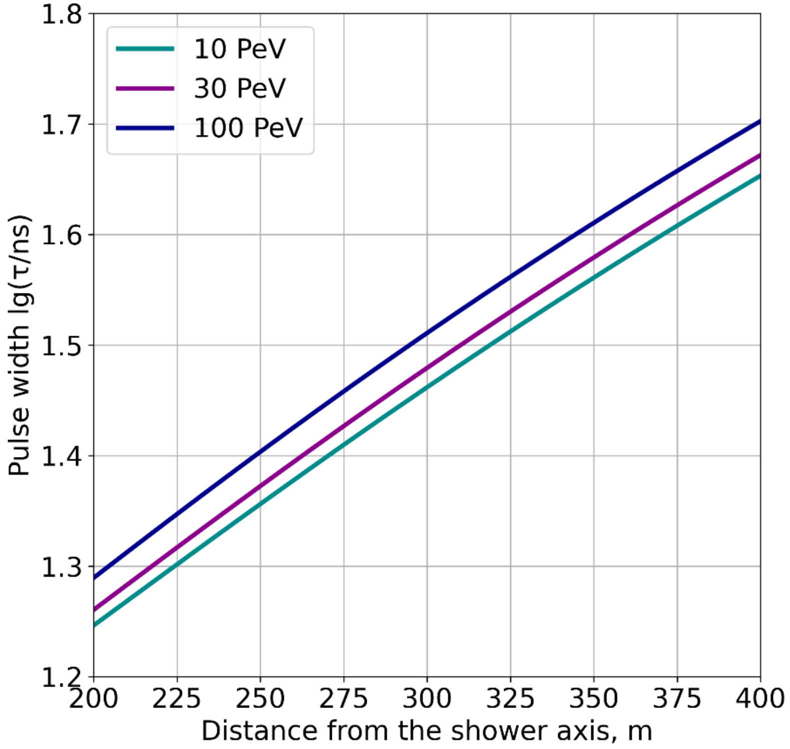
    - To account for instrumental effects, pulses from simulations (CORSIKA) are convolved with these characteristics to reproduce their behavior in the real experiment.





τ-Method for Determining X_{max}



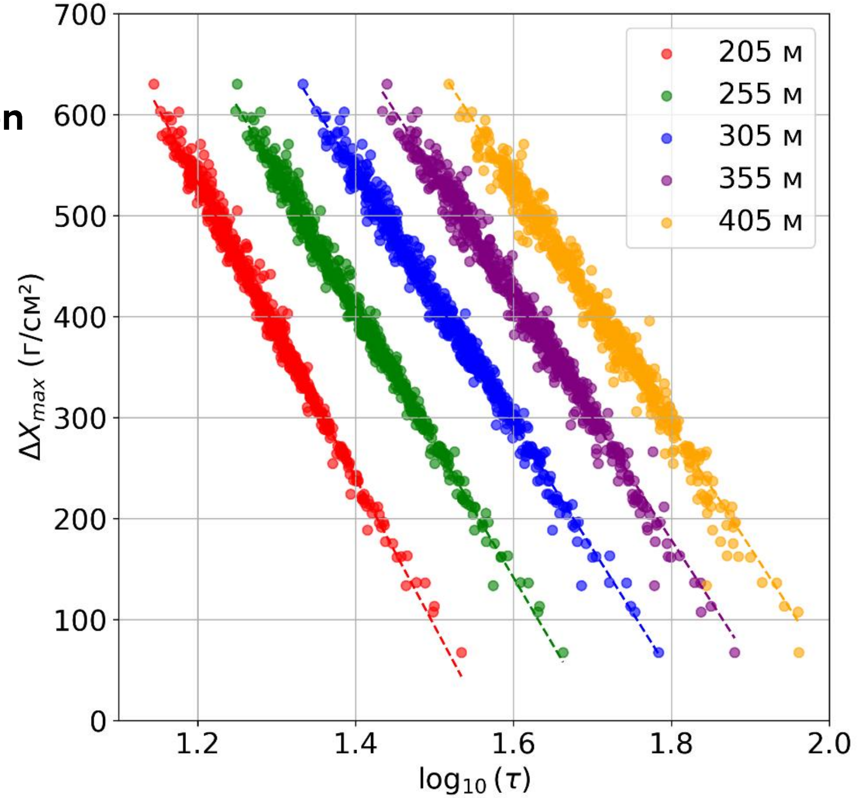


- **According to simulation data, pulse duration increases with distance.**

τ-Method for Determining X_{max}

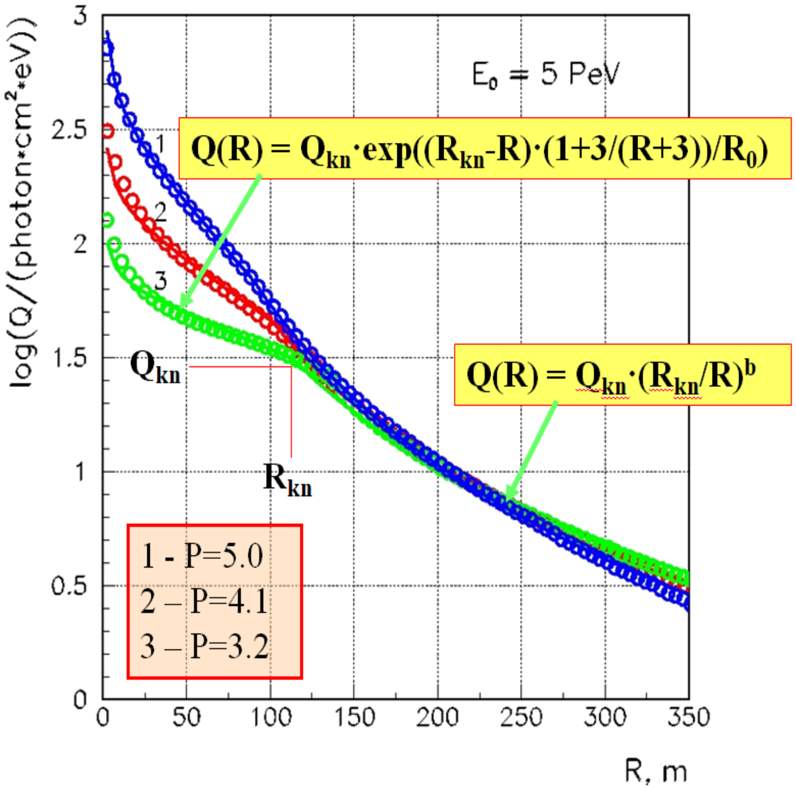
- **Point distributions are compiled from primary compositions for energies of 10, 30, 100 PeV and two angles (0-30°), with an instrumental function of FWHM = 9.2 ns.**

- **Anode Channel:**
  - 205 м: $\Delta X_{max} = -1465.0 \cdot \log\tau + 2291.1$,
  - 255 м: $\Delta X_{max} = -1333.2 \cdot \log\tau + 2274.8$, σ= ± 10.17 g/cm^2
  - **305 м:** $\boldsymbol{\Delta X_{max} = -1244.3 \cdot \log\tau + 2285.5}$, **σ = ± 11.30 g/cm²**
  - 355 м: $\Delta X_{max} = -1212.3 \cdot \log\tau + 2360.9$,
  - 405 м: $\Delta X_{max} = -1205.7 \cdot \log\tau + 2462.0$,



Correlation of X_{max} Relative Position and LDF Steepness

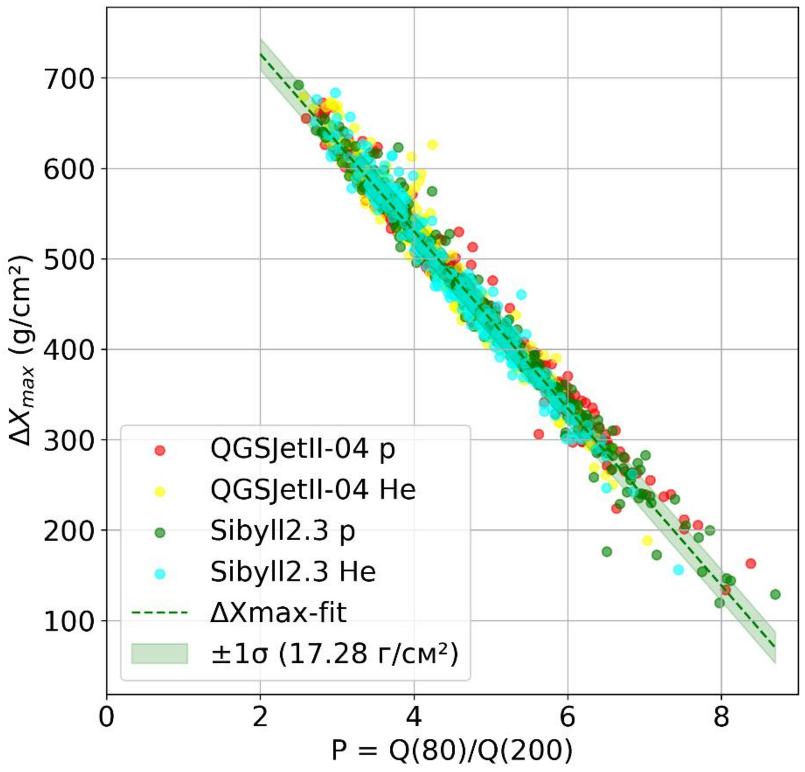
- Steepness: $P = Q(80)/Q(200)$ (parameter introduced in 2021);
- Relative position of the maximum: $\Delta X_{max} = X_0/\cos\theta - X_{max}$ (relative to the observation array);
- The shower maximum depth is determined using the ratio of light flux at distances of 80 and 200 m from the axis.



P vs ΔX_{max} Dependence

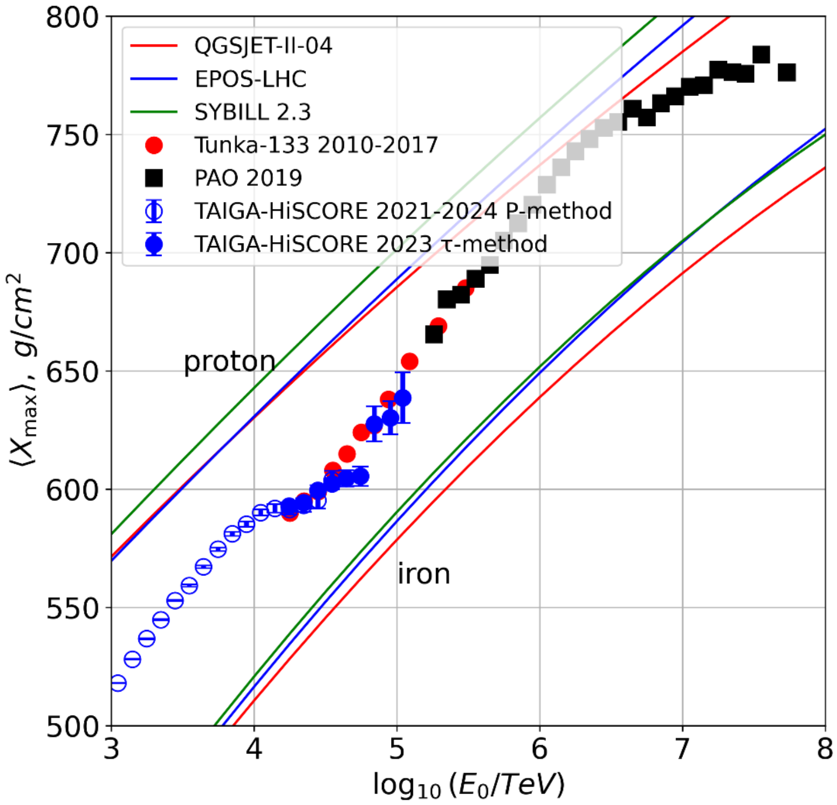
- Good fit, only p+He, 0-30°:
  $\Delta X_{max} = -98 \cdot P + 922$, σ= ±17.28 g/cm²

- 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^{16} eV),
  - Zenith angle of the shower (0° - 30°),
  - Hadron interaction model.



Experimental Dependence of $\langle X_{max} \rangle$ on Primary Energy

- **TAIGA-HiSCORE:**
  - For the **τ-method**: vertical configuration of the 2022-2023 season, 3383 events in the 10-130 PeV range;
  - 29 events above 100 PeV, 844 events at >30 PeV.
  - For the **P-method**: 2021-2024 seasons, 905283 events <30 PeV.
  - 4 clusters (114 stations);
  - Zenith angles $\theta \leq 30°$;
  - Effective area 1 km².



Average Mass Composition $\langle \ln A \rangle$

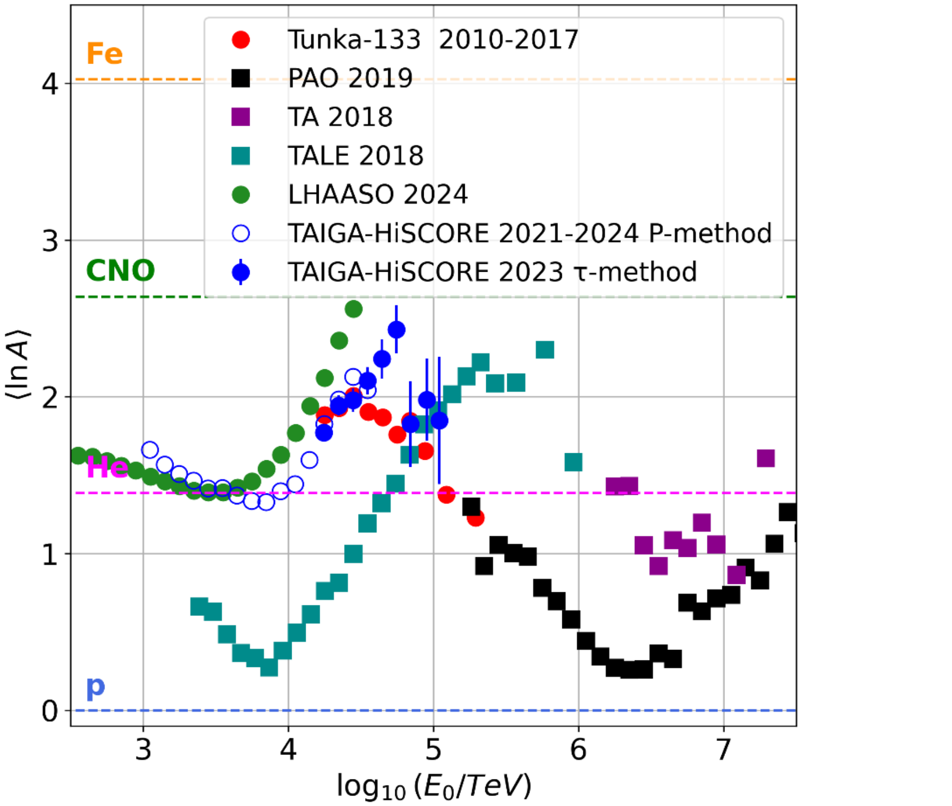
- Direct dependence $\langle \ln A \rangle \sim \langle X_{max} \rangle$ by linear interpolation:

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

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

- For comparison, data from the LHAASO, Pierre Auger Observatory, Telescope Array, TALE and Tunka-133 experiments were used.

- Across the entire energy range, a slightly lighter composition (p + He) is observed, but there is a range where the composition becomes heavier.



Conclusion

- Two independent methods for reconstructing the EAS maximum depth (X_{max}) based on TAIGA-HiSCORE data have been developed:
    - The **P-method**, using the steepness parameter of the Cherenkov light spatial distribution function ($P = Q(80)/Q(200)$),
    - The **τ-method**, based on the pulse width at a distance of 305 m from the shower axis.

- Linear dependencies for converting parameters P and τ_{305} to ΔX_{max} were established through CORSIKA shower simulations, with a reconstruction accuracy of 10–17 g/cm².
    - For the τ-method, the experimental statistics will increase by 3 times; new improvement - take into account noises for pulses in simulations."

- Based on TAIGA-HiSCORE data from the 2021–2024 seasons, the average maximum depth $\langle X_{max} \rangle$ and the average logarithm of the atomic number $\langle \ln A \rangle$ were determined, confirming the heavier composition of cosmic rays in the $3 \cdot 10^{15}$– $3 \cdot 10^{16}$ eV range and its lighter composition at energies above $3 \cdot 10^{16}$ eV.