# TAIGA experiment new results and development prospects

© N. Budnev,[1] L. Kuzmichev,[2] I. Astapov,[3] P. Bezyazeekov,[5] A. Blinov,[5] A. Borodin,[5] A. Bulan,[2] P. Busygin,[1] N. Volkov,[6] P. Volchugov,[1,2] D. Voronin,[7] A. Gafarov,[1] A. Garmash,[4,8] G.S. Goman,[2] V. Grebenyuk,[5,7] O. Gress,[1] T. Gress,[1] E. Gress,[1] A. Grinyuk,[5] O. Grishin,[1] A. Dyachok,[1] D. Zhurov,[1] A. Zagorodnikov,[1] V. Zirakashvilli,[12] A.D. Ivanova,[1,10] A.L. Ivanova,[1,4] M. Ilyushin,[1] N. Kalmykov,[2] V. Kindin,[3] S. Kiryukhin,[2] V. Kozhin,[2] K. Kompaniets,[3] E. Korosteleva,[2] E. Kravchenko,[4,8] A. Kryukov,[2] A. Chiavassa,[11] A. Lagutin,[6] Yu. Lemeshev,[1] B. Lubsandorzhiev,[7] N. Lubsandorzhiev,[1,2] S. Malakhov,[1] R. Mirgazov,[1] R. Monkhoev,[1] E. Okuneva,[1,2] E. Osipova,[2] A. Pan,[5] A. Panov,[2] L. Pankov,[1] A. Pakhorukov,[1] A. Petrukhin,[3] V. Poleschuk,[1] E. Popova,[2] E. Postnikov,[2] V. Prosin,[1,2] A. Pushnin,[1] R. Raikin,[6] A. Razumov,[2] G. Rubtsov,[7] E. Ryabov,[1] I. Satyshev,[5] V. Samoliga,[1] L. Sveshnikova,[2] A. Sidorenkov,[7] A. Silaev,[2] A. Silaev (junior),[2] A. Skurikhin,[2] A. Sokolov,[4,8] V. Tabolenko,[1] M. Ternovoy,[1] N. Ushakov,[7] A. Shaykovsky,[5] M. Shulga,[1] I. Yashin[3]

[1]Irkutsk State University,
664003 Irkutsk, Russia
[2]Skobeltsyn Institute of Nuclear Physics, Moscow State University,
119991 Moscow, Russia
[3]National Research Nuclear University „MEPhI",
115409 Moscow, Russia
[4]Novosibirsk State University,
630090 Novosibirsk, Russia
[5]Joint Institute for Nuclear Research,
141980 Dubna, Moscow oblast, Russia
[6]Altai State University,
656049 Barnaul, Russia
[7]Institute for Nuclear Research, Russian Academy of Sciences,
117312 Troitsk, Moscow, Russia
[8]Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia
[9]Dubna State University,
141980 Dubna, Moscow oblast, Russia
[10]Moscow Institute of Physics and Technology (National Research University),
117303 Dolgoprudny, Moscow Region, Russia
[11]University of Torino,
Turin, Italy
[12]Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS,
142190 Moscow, Russia
e-mail: nbudnev@api.isu.ru

*Received May 5, 2025*
*Revised July 14, 2025*
*Accepted July 14, 2025*

The article presents some of the latest results of studies of cosmic ray and gamma-ray fluxes obtained using the TAIGA-1 hybrid complex, and proposals for the creation of the TAIGA-100 complex with an area of 100 km$^2$ about.

**Keywords:** TAIGA, cosmic rays, gamma-ray astronomy, energy spectrum.

DOI: 10.61011/TP.2025.12.62392.237-25

## Introduction

It is very important to investigate fluxes of neutral particles — gamma quanta and neutrinos, for studying a nature of sources of high-energy primary cosmic rays (PCR). At the first stage of development of ground-based high-energy gamma-astronomy, the basic results were obtained by means of facilities H.E.S.S, MAGIC and VERITAS, which included from 2 to 5 so-called IACTs (Imaging Atmospheric Cherenkov Telescopes). However, a limited sizes of the effective area (below 0.1 km$^2$) of these facilities does not allow recording gamma quanta with the energy of higher than 100 TeV with significant statistics. Breakthrough in studying astrophysical sources, in which the particles are accelerated to energies of about 1 PeV and higher (PeVatrons), occurred with start of operation of high-altitude facilities designed to record EAS charged particles of (extensive air showers): Tibet-ASgamma, HAWC and LHASSO. They were used to record the gamma quanta with the energy of higher than 100 TeV from more than forty galactical sources and to record the gamma quanta with the energy of higher than 1 PeV [1] from two sources (the Crab Nebula and J2032+4102).

In recent years, a complex TAIGA-1 started taking data [2] in the Tunka Valley, 50 km from the lake Baikal. Its effective area for recording the gamma quanta with the energy of higher than 100 TeV is about 1 km$^2$, thereby making it possible to start studying the PeVatrons by recording EAS Cherenkov radiation for the first time. The present study presents some of the latest results obtained by means of the TAIGA-1 complex and suggestions for creating the TAIGA-100 complex of the area of about 100 km$^2$.

## 1. Studies of the PCR fluxes

An energy spectrum and a mass composition of the PCRs are studied by means of all the facilities of the TAIGA complex within the energy range from 10 TeV to 1000 PeV. It is especially interesting to study a nature of break of the PCR energy spectrum within a „classic knee" at the energy of 3 PeV, whose nature is still uncertain, a decrease of spectrum inclination at the energy 20–30 PeV and an issue of whether an increase of spectrum slope at the energy of 100 PeV indicates a transition from galactic to extragalactic PCR?

When processing the data from facility Tunka-133 that is commissioned in 2009 and has an energy threshold of about 8 PeV, a main parameter for restoring the EAS energy is a photon flux at the distance of 200 m from the EAS axis Q(200) [3]. A wide-angle Cherenkov TAIGA-HiSCORE facility [2] has a lower threshold (of about 200 TeV) for PCR recording. With these energies, the photon flux from the PSBs is significantly smaller, therefore, a new method of energy restoration has been developed, in which along with the parameter Q(200) a density of the Cherenkov photon flux at the distance of 100 m from the EAS axis Q(100) is used.

Fig. 1 shows the PCR energy spectrum constructed as a result of processing new experimental data that are obtained during synchronous operations of all four clusters of the TAIGA-HiSCORE facility for the seasons of 2022–2024 and of reprocessing the previously-obtained ones. The data were process using, in particular, the new parameter Q(100). Recording efficiency of more than 95 % starts for the energies above 300 TeV. The energy spectrum has a power-law shape $E^{\gamma}$ and includes about 18 million events. The spectrum well exhibits an increase of slope at the energy of 3 PeV and a decrease of slope at the energy of 20 PeV. The spectrum inclination index $\gamma = (3.12 \pm 0.01)$ within the range 3–20 PeV, $\gamma = 2.97 - 0.03)$ within the range 20–100 PeV and $\gamma = (3.3 \pm 0.2)$ above 100 PeV. Our new spectra are close to the spectra obtained in the LHAASO facility by another procedure [4].

Fig. 2, *a* shows results of determination of the average depth of the EAS maximum Xmax according to the data from the TAIGA-HiSCORE facility for a vertical direction of the optical stations for the seasons of measurements

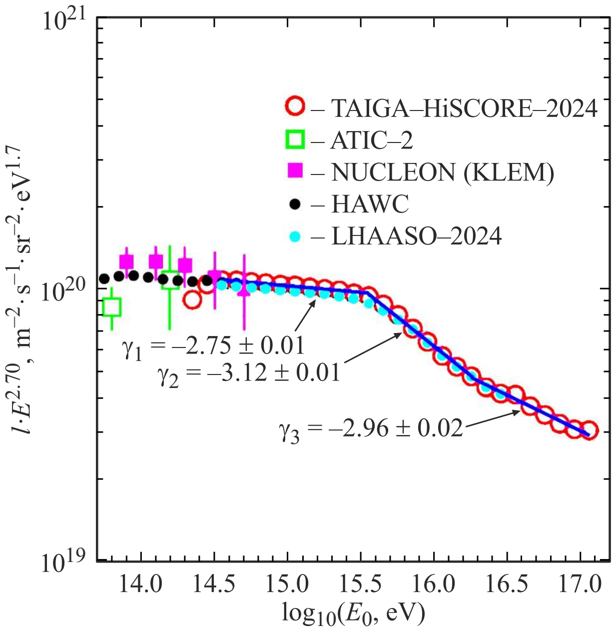


**Figure 1.** Energy spectrum of the cosmic rays according to the data of the TAIGA-HiSCORE facility as compared to the results of the other facilities. Approximation of data with the power law $E^{\gamma}$ with respective values of an energy spectrum's inclination index $\gamma$.

during 2022–2024. The value of $X_{\max}$ is unambiguously related to slope of a spatial distribution function (SDF) and duration of Cherenkov light pulses at the large distances from the axis. The SDF slope was determined using the parameter $P$, which is „a ratio of the density of the Cherenkov light flux at the distance of 80 m to the light flux density at the distance of 200 m, $P = Q(80)/Q(200)$. The same figure compares the new results as per data of the TAIGA-HiSCORE facility with the results of the Tunka-133 facility, which are recalculated by the same procedure, and with results of experiments RAO [5] and TA [6], which are obtained by observing EAS fluorescent light. Fig. 2, *b* shows an average logarithm of the mass of the primary cosmic rays $\langle \ln \mathrm{A} \rangle$, which is recalculated as per data about $X_{\max}$ by linear interpolation between calculated dependences of the depth of the EAS maximum, depending on the energy for primary protons and iron nuclei. At the same time, calculated curves have been used for the model QGSJET-II-04 [7]. Around the „knee" our data on the PCR mass composition (Fig. 2, *b*) are also close to LHAASO results. Certain lightening is observed below the energy of 3 PeV, so is weighting thereabove.

## 2. Energy spectrum of gamma-radiation of the Crab Nebula

A typical distance between the five Imaging Atmospheric Cherenkov telescopes (IACT) [2] of the TAIGA-IACT facility is about 250 m [8] (currently, four IACTs are involved in data gaining, the fifth telescope will be commissioned in

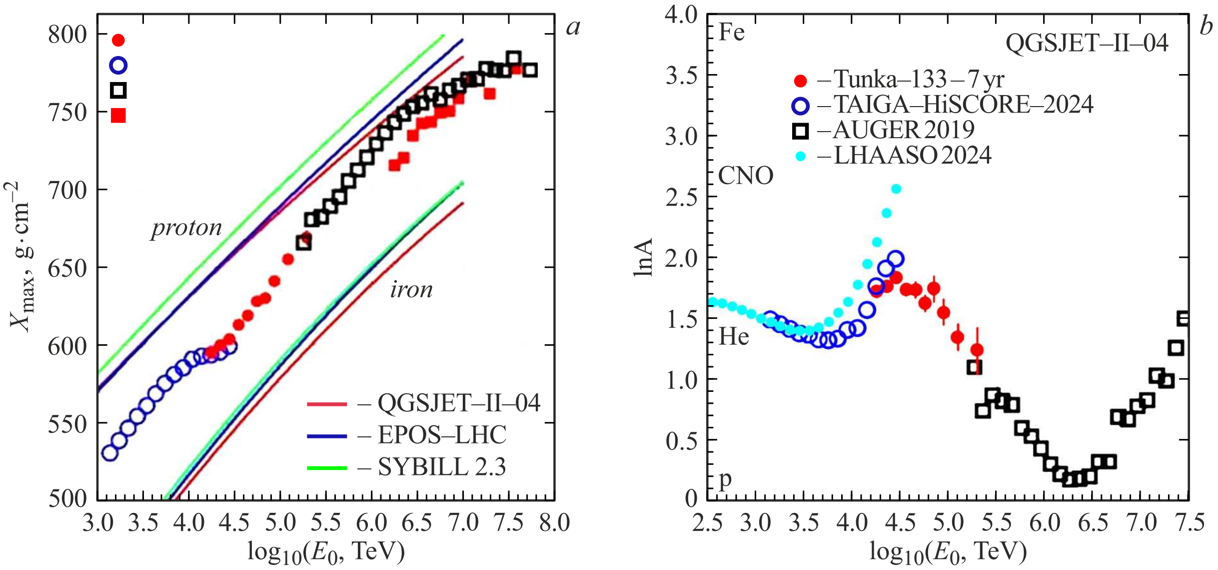


**Figure 2.** *a* is a depth of the EAS maximum; *b* is an average logarithm of the mass number, which is averaged over the composition of the cosmic rays according to the data of the facilities TAIGA-HiSCORE and Tunka-133.

the nearest two years). The facility can record the gamma quanta in a stereoscopic mode with the energy of more than 10 TeV. Procedures for determination of the energy and $X_{max}$ of the events are realized by means of the framework Light Gradient-Boosting Machine (LGBM) (fast implementation of the GBDT algorithm), which makes it possible to create and tune a set of successively learning solution trees. For the gamma quanta with the energy of more than 20 TeV, energy resolution is $\sim$ 20 %, while restoration accuracy $X_{max}$ is better than 20 g/cm$^2$.

A procedure of distinguishing the gamma quanta with the energies of higher than 10 TeV includes selection of the event by the parameters: width — a normalized width and $\theta^2$ — an angle between a restored EAS arrival direction and a direction towards the observed gamma-quantum source (see [9] for more details). Optimal values of selection criteria are determined based on Monte–Carlo simulation

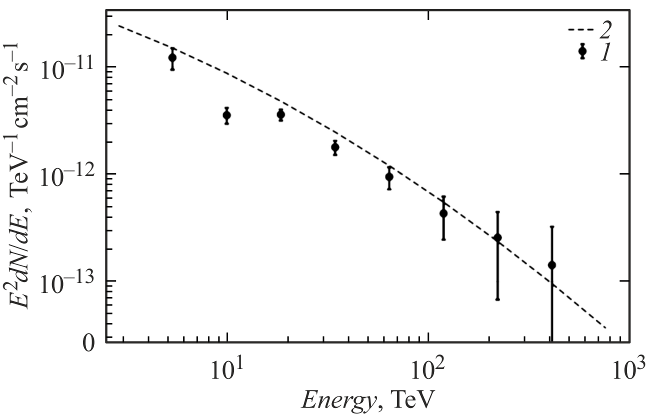


**Figure 3.** *1* — the energy spectrum of the Crab Nebula as per the data of the TAIGA-IACT facility; *2* — approximation of the energy spectrum of this source, which is obtained by the LHAASO observatory in the study [4].

by maximizing a Q-factor, which is a ratio of a portion of the gamma-quanta EAS-selected ones to a root of the hadron EAS-selected ones. This approach made it possible to achieve hadron EAS suppression in $10^4$ times. The respective selection criteria are nwidth$< 0.4$ and $\theta^2 < 0.04$. Significance of the obtained excess of gamma radiation from the Crab Nebula is up to $\sim 12\sigma$. The energy spectrum of gamma radiation of the Crab Nebula, which is constructed by observation data by means of the TAIGA-IACT facility in a stereo mode during 234 h for the period 2020–2023, is shown in Fig. 3 [10].

The spectrum includes 5 gamma-like events with the energy of more than 100 TeV. Two points with the energies of below 10 TeV were obtained in the season during 2022–2023, when the telescopes were updated and sensitivity of the TAIGA-IACT facility increased.

## 3. TAIGA-100 — the hybrid facility for multi-PeV gamma-astronomy

A project of the future TAIGA-100 complex with a hybrid detector system on the area of about 100 km$^2$ is optimized for studying the fluxes of cosmic rays and gamma quanta within the energy range from portions of PeV to tens of EeV. The basic elements of the complex will be wide-angle Cherenkov stations with a view angle of $\sim$ 1 sr and water Cherenkov muon detectors with the area of about 40 m$^2$ each. The energy threshold of the system of these detectors will be about 300 TeV. When observing the local sources by this facility, the expected statistics of gamma quanta with the energy of more than 0.5 PeV will be in 1–5 times higher than by LHAASO. In particular, it will allow recording more than 100 gamma quanta with the energy of more than 500 TeV for 100 h of observations. In order to solve gamma-astronomy tasks with the lower energies and to search for gamma quanta of the sub-TeV energy from gamma-ray bursts, the complex will include about 10 IACTs with the mirrors of the 4-m diameter (as in the TAIGA-1 facility) and 2 IACTs with the diameter of about 10 m. In order to study high-energy cosmic rays, the complex will include scintillation detectors, two fluorescent-radiation telescopes and radio antennas.

In order to refine methodological and technical issues and to demonstrate efficiency of the TAIGA-100 complex for solving tasks of super-high-energy gamma-astronomy and cosmic-ray physics, it is planned to create an operable prototype of the area of 0.5 $km^2$ by 2029 on a site of the TAIGA-1 complex in the Tunka valley. According to the results of preliminary studies, the most promising site in terms of a set of natural and infrastructural factors for creating the full-scale TAIGA-100 complex is the Borgoy steppe in the Republic of Buryatia (about 200 km south of the Ulan-Ude city).

### Funding

The study was conducted on the Unique Research System „Astrophysical System of Moscow State University-Irkutsk State University“ and supported by the Russian Science Foundation: grant 23-72-016 (Section „Studies of fluxes of primary cosmic rays“, grant 23-72-00019 (Section „Energy spectrum of gamma-radiation of the Crab Nebula“) and the Ministry of Education and Science of the Russian Federation (FZZE-2026-0006, FZZE-2024-0005).

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] Zh. Cao, F. Aharonian, Q. An, Axikegu, Y.X. Bai, Y.W. Bao, D. Bastieri, X.J. Bi, Y.J. Bi, J.T. Cai, Q. Cao, W.Y. Cao, Zh. Cao, J. Chang, J.F. Chang, A.M. Chen, E.S. Chen, Liang Chen, Lin Chen, Long Chen, M.J. Chen, M.L. Chen, Q.H. Chen, S.H. Chen, S.Z. Chen, T.L. Chen, Y. Chen, N. Cheng, Y.D. Cheng, M.Y. Cui, S.W. Cui, X.H. Cui, Y.D. Cui, B.Z. Dai, H.L. Dai, Z.G. Dai, Danzengluobu, D. della Volpe, X.Q. Dong, K.K. Duan, J.H. Fan, Y.Z. Fan, J. Fang, K. Fang, C.F. Feng, L. Feng, S.H. Feng, X.T. Feng, Y.L. Feng, S. Gabici, B. Gao, C.D. Gao, L.Q. Gao, Q. Gao, W. Gao, W.K. Gao, M.M. Ge, L.S. Geng, G. Giacinti, G.H. Gong, Q.B. Gou, M.H. Gu, F.L. Guo, X.L. Guo, Y.Q. Guo, Y.Y. Guo, Y.A. Han, H.H. He, H. N. He, J. Y. He, X. B. He, Y. He, M. Heller, Y.K. Hor, B.W. Hou, C. Hou, X. Hou, H.B. Hu, Q. Hu, S.C. Hu, D.H. Huang, T.Q. Huang, W.J. Huang, X.T. Huang, X.Y. Huang, Y. Huang, Z.C. Huang, X.L. Ji, H.Y. Jia, K. Jia, K. Jiang, X.W. Jiang, Z.J. Jiang, M. Jin, M.M. Kang, T. Ke, D. Kuleshov, K. Kurinov, B.B. Li, Ch. Li, C. Li, D. Li, F. Li, H.B. Li, H.C. Li, H.Y. Li, J. Li, Ji. Li, Jie Li, K. Li, W.L. Li, W.L. Li, X.R. Li, Xin Li, Y.Z. Li, Zhe Li, Zhuo Li, E.W. Liang, Y.F. Liang, S.J. Lin, B. Liu, C. Liu, D. Liu, H. Liu, H.D. Liu, J. Liu, J.L. Liu, J.Y. Liu, M.Y. Liu, R.Y. Liu, S.M. Liu, W. Liu, Y. Liu, Y.N. Liu, R. Lu, Q. Luo, H.K. Lv, B.Q. Ma, L.L. Ma, X.H. Ma, J.R. Mao, Z. Min, W. Mitthumsiri, H.J. Mu, Y.C. Nan, A. Neronov, Z.W. Ou, B.Y. Pang, P. Pattarakijwanich, Z.Y. Pei, M.Y. Qi, Y.Q. Qi, B.Q. Qiao, J.J. Qin, D. Ruffolo, A. Sáiz, D. Semikoz, C.Y. Shao, L. Shao, O. Shchegolev, X.D. Sheng, F.W. Shu, H.C. Song, Yu.V. Stenkin, V. Stepanov, Y. Su, Q.N. Sun, X. N. Sun, Z.B. Sun, P.H.T. Tam, Q.W. Tang, Z.B. Tang, W.W. Tian, C. Wang, C.B. Wang, G.W. Wang, H.G. Wang, H.H. Wang, J.C. Wang, K. Wang, L.P. Wang, L.Y. Wang, P.H. Wang, R. Wang, W. Wang, X.G. Wang, X.Y. Wang, Y. Wang, Y.D. Wang, Y.J. Wang, Z.H. Wang, Z.X. Wang, Zhen Wang, Zheng Wang, D.M. Wei, J.J. Wei, Y.J. Wei, T. Wen, C.Y. Wu, H.R. Wu, S. Wu, X. F. Wu, Y.S. Wu, S.Q. Xi, J. Xia, J.J. Xia, G.M. Xiang, D.X. Xiao, G. Xiao, G.G. Xin, Y.L. Xin, Y. Xing, Z. Xiong, D.L. Xu, R.F. Xu, R.X. Xu, W.L. Xu, L. Xue, D.H. Yan, J.Z. Yan, T. Yan, C.W. Yang, F. Yang, F.F. Yang, H.W. Yang, J.Y. Yang, L.L. Yang, M.J. Yang, R.Z. Yang, S.B. Yang, Y.H. Yao, Z.G. Yao, Y.M. Ye, L.Q. Yin, N. Yin, X.H. You, Z.Y. You, Y.H. Yu, Q. Yuan, H. Yue, H.D. Zeng, T.X. Zeng, W. Zeng, M. Zha, B.B. Zhang, F. Zhang, H.M. Zhang, H.Y. Zhang, J.L. Zhang, L.X. Zhang, Li Zhang, P. F. Zhang, P. P. Zhang, R. Zhang, S. B. Zhang, S. R. Zhang, S. S. Zhang, X. Zhang, X.P. Zhang, Y. F. Zhang, Yi Zhang, Yong Zhang, B. Zhao, J. Zhao, L. Zhao, L.Z. Zhao, S.P. Zhao, F. Zheng, B. Zhou, H. Zhou, J.N. Zhou, M. Zhou, P. Zhou, R. Zhou, X.X. Zhou, C.G. Zhu, F.R. Zhu, H. Zhu, K. J. Zhu, X. Zuo, The LHAASO Collaboration. Astrophys. J. Supplement Series, **271** (1), 25 (2024).
DOI: 10.3847/1538-4365/acfd29

[2] N. Budnev, I. Astapov, P. Bezyazeekov, E. Bonvech, V. Boreyko, A. Borodin, M. Brü ckner, A. Bulan, D. Chernov, D. Chernykh, A. Chiavassa, A. Dyachok, O. Fedorov, A. Gafarov, A. Garmash, V. Grebenyuk, O. Gress, T. Gress, A. Grinyuk, O. Grishin, D. Horns, A. Ivanova, N. Kalmykov, Y. Kazarina, V. Kindin, S. Kiryuhin, R. Kokoulin, K. Kompaniets, D. Kostunin, E. Korosteleva, V. Kozhin, E. Kravchenko, A. Kryukov, L. Kuzmichev, A. Lagutin, Yu. Lemeshev, B. Lubsandorzhiev, N. Lubsandorzhiev, R. Mirgazov, R. Mirzoyan, R. Monkhoev, E. Osipova, A. Pakhorukov, A. Pan, M. Panasyuk, L. Pankov, D. Podgrudkov, V. Poleschuk, M. Popesku, E. Popova, A. Porelli, E. Postnikov, V. Prosin, V. Ptuskin, A. Petrukhin, A. Pushnin, R. Raikin, E. Rjabov, G. Rubtsov, Y. Sagan, V. Samoliga, A. Sidorenkov, A. Silaev, A. Silaev (junior), A. Skurikhin, M. Slunecka, A. Sokolov, L. Sveshnikova, Y. Suvorkin, V. Tabolenko, A. Tanaev, B. Tarashansky, L. M.Ternovoy, A. Tkachenko, L. Tkachev, M. Tluczykont, N. Ushakov, A. Vaidyanathan, P. Volchugov, D. Voronin, R. Wischnewski, I. Yashin, A. Zagorodnikov, D. Zhurov. JINST, **15** (9), C09031 (2020). DOI: 10.1088/1748-0221/15/09/C09031.

[3] N.M. Budnev, A. Chiavassa, O.A. Gress, T.I. Gress, A.N. Dyachok, N.I. Karpov, N.N. Kalmykov, E.E. Korosteleva, V.A. Kozhin, L.A. Kuzmichev, B.K. Lubsandorzhiev, N.B. Lubsandorzhiev, R.R. Mirgazov, E.A. Osipova, M.I. Panasyuk, L.V. Pankov, E.G. Popova, V.V. Prosin, V.S. Ptuskin, Yu.A. Semeney, A.V. Zagorodnikov. Astroparticle Phys., **117** 102406, (2020).
DOI: 10.1016/j.astropartphys.2019.102406

[4] W. Bian, A.V. Bukevich, Q. Cao, W.Y. Cao, Zhe Cao, J. Chang, J.F. Chang, A.M. Chen, E.S. Chen, H.X. Chen, Liang Chen, Lin Chen, Long Chen, M.J. Chen, M.L. Chen, Q.H. Chen, S. Chen, S.H. Chen, S.Z. Chen, T.L. Chen, Y. Chen, N. Cheng, Y.D. Cheng, M.Y. Cui, S.W. Cui, X.H. Cui, Y.D. Cui,

B.Z. Dai, H.L. Dai, Z.G. Dai, Danzengluobu, X.Q. Dong, K.K. Duan, J.H. Fan, Y.Z. Fan, J. Fang, J.H. Fang, K. Fang, C.F. Feng21, H. Feng, L. Feng, S.H. Feng, X.T. Feng, Y. Feng, Y.L. Feng, S. Gabici, B. Gao, C.D. Gao, Q. Gao, W. Gao, W.K. Gao, M.M. Ge, L.S. Geng, G. Giacinti, G.H. Gong, Q.B. Gou, M.H. Gu, F.L. Guo, X.L. Guo, Y.Q. Guo, Y.Y. Guo, Y.A. Han, M. Hasan, H.H. He, H.N. He, J.Y. He, Y. He, Y.K. Hor, B.W. Hou, C. Hou, X. Hou, H.B. Hu, Q. Hu, S.C. Hu, D.H. Huang, T.Q. Huang, W.J. Huang, X.T. Huang, X.Y. Huang, Y. Huang, X.L. Ji, H.Y. Jia, K. Jia, K. Jiang, X.W. Jiang, Z.J. Jiang, M. Jin, M.M. Kang, I. Karpikov, D. Kuleshov, K. Kurinov, B.B. Li, C.M. Li, Cheng Li, Cong Li, D. Li, F. Li, H.B. Li, H.C. Li, Jian Li, Jie Li, K. Li, S.D. Li, W.L. Li, W.L. Li, X.R. Li, Xin Li, Y.Z. Li, Zhe Li, Zhuo Li, E.W. Liang, Y.F. Liang, S.J. Lin, B. Liu, C. Liu, D. Liu, D.B. Liu, H. Liu, H.D. Liu, J. Liu, J.L. Liu, M.Y. Liu, R.Y. Liu, S.M. Liu, W. Liu, Y. Liu, Y.N. Liu, Q. Luo, Y. Luo, H.K. Lv, B.Q. Ma, L.L. Ma, X.H. Ma, J.R. Mao, Z. Min, W. Mitthumsiri, H.J. Mu, Y.C. Nan, A. Neronov, L.J. Ou, P. Pattarakijwanich, Z.Y. Pei, J.C. Qi, M.Y. Qi, B.Q. Qiao, J.J. Qin, A. Raza, D. Ruffolo, A. Sáiz, M. Saeed, D. Semikoz, L. Shao, O. Shchegolev, X.D. Sheng, F.W. Shu, H.C. Song, Yu.V. Stenkin, V. Stepanov, Y. Su, D.X. Sun, Q.N. Sun, X.N. Sun, Z.B. Sun, J. Takata, P.H.T. Tam, Q.W. Tang, R. Tang, Z.B. Tang, W.W. Tian, C. Wang, C.B. Wang, G.W. Wang, H.G. Wang8, H.H. Wang, J.C. Wang, Kai Wang, Kai Wang, L.P. Wang, L.Y. Wang, P.H. Wang, R. Wang, W. Wang, X.G. Wang, X.Y. Wang, Y. Wang, Y.D. Wang, Y.J. Wang, Z.H. Wang, Z.X. Wang, Zhen Wang, Zheng Wang, D.M. Wei, J.J. Wei, Y.J. Wei, T. Wen, C.Y. Wu, H.R. Wu, Q.W. Wu, S. Wu, X.F. Wu, Y.S. Wu, S.Q. Xi, J. Xia, G.M. Xiang, D.X. Xiao, G. Xiao, Y.L. Xin, Y. Xing, D.R. Xiong, Z. Xiong, D.L. Xu, R.F. Xu, R.X. Xu, W.L. Xu, L. Xue, D.H. Yan, J.Z. Yan, T. Yan, C.W. Yang, C.Y. Yang, F. Yang, F.F. Yang, L.L. Yang, M.J. Yang, R.Z. Yang, W.X. Yang, Y.H. Yao, Z.G. Yao, L.Q. Yin, N. Yin, X.H. You, Z.Y. You, Y.H. Yu, Q. Yuan, H. Yue, H.D. Zeng, T.X. Zeng, W. Zeng, M. Zha, B.B. Zhang, F. Zhang, H. Zhang, H.M. Zhang, H.Y. Zhang, J.L. Zhang, Li Zhang, P.F. Zhang, P.P. Zhang, R. Zhang, S.B. Zhang, S.R. Zhang, S.S. Zhang, X. Zhang, X.P. Zhang, Y.F. Zhang, Yi Zhang, Yong Zhang, B. Zhao, J. Zhao, L. Zhao, L.Z. Zhao, S.P. Zhao, X.H. Zhao, F. Zheng, W.J. Zhong, B. Zhou, H. Zhou, J.N. Zhou, M. Zhou, P. Zhou, R. Zhou, X.X. Zhou, X.X. Zhou, B.Y. Zhu, C.G. Zhu, F.R. Zhu, H. Zhu, K.J. Zhu, Y.C. Zou, X. Zuo. Phys. Rev. Lett., **132**, 131002 (2024). DOI: 10.1103/PhysRevLett.132.131002

[5] A. Yushkov, A. Aab, P. Abreu, M. Aglietta, I.F.M. Albuquerque, J.M. Albury, I. Allekotte, A. Almela, J. Alvarez Castillo, J. Alvarez-Muñiz, G.A. Anastasi, L. Anchordoqui, B. Andrada, S. Andringa, C. Aramo, H. Asorey, P. Assis, G. Avila, A.M. Badescu, A. Bakalova, A. Balaceanu, F. Barbato, R.J. Barreira Luz, S. Baur, K.H. Becker, J.A. Bellido, C. Berat, M.E. Bertaina, X. Bertou, P.L. Biermann, T. Bister, J. Biteau, A. Blanco, J. Blazek, C. Bleve, M. Boháčová, D. Boncioli, C. Bonifazi, N. Borodai, A.M. Botti, J. Brack, T. Bretz, F.L. Briechle, P. Buchholz, A. Bueno, S. Buitink, M. Buscemi, K.S. Caballero-Mora, L. Caccianiga, L. Calcagni, A. Cancio, F. Canfora, I. Caracas, J.M. Carceller, R. Caruso, A. Castellina, F. Catalani, G. Cataldi, L. Cazon, M. Cerda, J.A. Chinellato, K. Choi, J. Chudoba, L. Chytka, R.W. Clay, A.C. Cobos Cerutti, R. Colalillo, A. Coleman, M.R. Coluccia, R. Conceiçã o, A. Condorelli, G. Consolati, F. Contreras, F. Convenga, M.J. Cooper, S. Coutu, C.E. Covault, B. Daniel, S. Dasso, K. Daumiller, B.R. Dawson, J.A. Day, R.M. de Almeida, S.J. de Jong, G. De Mauro, J.R.T. de Mello Neto, I. De Mitri, J. de Oliveira, V. de Souza, J. Debatin, M. del Río, O. Deligny, N. Dhital, A. Di Matteo, M.L. Díaz Castro, C. Dobrigkeit, J.C. D'Olivo, Q. Dorosti, R.C. dos Anjos, M.T. Dova, A. Dundovic, J. Ebr, R. Engel, M. Erdmann, C.O. Escobar, A. Etchegoyen, H. Falcke, J. Farmer, G. Farrar, A.C. Fauth, N. Fazzini, F. Feldbusch, F. Fenu, L.P. Ferreyro, J.M. Figueira, A. Filipč ič, M.M. Freire, T. Fujii, A. Fuster, B. García, H. Gemmeke, F. Gesualdi, A. Gherghel-Lascu, P.L. Ghia, U. Giaccari, M. Giammarchi, M. Giller, D. Głas, J. Glombitza, F. Gobbi, G. Golup, M. Gó mez Berisso, P.F. Gó mez Vitale, J.P. Gongora, N. González, I. Goos, D. Gó ra, A. Gorgi, M. Gottowik, T.D. Grubb, F. Guarino, G.P. Guedes, E. Guido, S. Hahn, R. Halliday, M.R. Hampe, P. Hansen, D. Harari, T.A. Harrison, V.M. Harvey, A. Haungs, T. Hebbeker, D. Heck, G.C. Hill, C. Hojvat, E.M. Holt, J.R. Hö randel, P. Horvath, M. Hrabovský, T. Huege, J. Hulsman, A. Insolia, P.G. Isar, J.A. Johnsen, J. Jurysek, A. Kää pä, K.H. Kampert, B. Keilhauer, N. Kemmerich, J. Kemp, H.O. Klages, M. Kleifges, J. Kleinfeller, G. Kukec Mezek, A. Kuotb Awad, B.L. Lago, D. LaHurd, R.G. Lang, R. Legumina, M.A. Leigui de Oliveira, V. Lenok, A. Letessier-Selvon, I. Lhenry-Yvon, O.C. Lippmann, D. Lo Presti, L. Lopes, R. Ló pez, A. Ló pez Casado, R. Lorek, Q. Luce, A. Lucero, M. Malacari, G. Mancarella, D. Mandat, B.C. Manning, J. Manshanden, P. Mantsch, A.G. Mariazzi, I.C. Mariş, G. Marsella, D. Martello, H. Martinez, O. Martínez Bravo, M. Mastrodicasa, H.J. Mathes, S. Mathys, J. Matthews, G. Matthiae, E. Mayotte, P.O. Mazurc, G. Medina-Tanco, D. Melo, A. Menshikov, K.-D. Merenda, S. Michal, M.I. Micheletti, L. Miramonti, D. Mockler, S. Mollerach, F. Montanet, C. Morello, G. Morlino, M. Mostafá, A.L. Müller, M.A. Muller, S. Müller, R. Mussa, W.M. Namasaka, L. Nellen, M. Niculescu-Oglinzanu, M. Niechciol, D. Nitz, D. Nosek, V. Novotny, L. Nožka, A Nucita, L.A. Núñez, A. Olinto, M. Palatka, J. PPallotta, M.P. Panetta, P. Papenbreer, G. Parente, A. Parra, M. Pech, F. Pedreira, J. Pękala, R. Pelayo, J. Peña-Rodriguez, L.A.S. Pereira, M. Perlin, L. Perrone, C. Peters, S. Petrera, J. Phuntsok, T. Pierog, M. Pimenta, V. Pirronello, M. Platino, J. Poh, B. Pont, M. Pothast, R.R. Prado, P. Privitera, M. Prouza, A. Puyleart, S. Querchfeld, R. Ramos-Pollan, J. Rautenberg, D. Ravignani, M. Reininghaus, J. Ridky, F. Riehn, M. Risse, P. Ristori, V. Rizi, W. Rodrigues de Carvalho, J. Rodriguez Rojo, M.J. Roncoroni, M. Roth, E. Roulet, A.C. Rovero, P. Ruehl, S.J. Saffi, A. Saftoiu, F. Salamida, H. Salazar, G. Salina, J.D. Sanabria Gomez, F. Sánchez, E.M. Santos, E. Santos, F. Sarazin, R. Sarmento, C. Sarmiento-Cano, R. Sato, P. Savina, M. Schauer, V. Scherini, H. Schieler, M. Schimassek, M. Schimp, F. Schlüter, D. Schmidt, O. Scholten, P. Schovánek, F.G. Schröder, S. Schröder, J. Schumacher, S.J. Sciutto, M. Scornavacche, R.C. Shellard, G. Sigl, G. Silli, O. Sima, R. Šmida, G.R. Snow, P. Sommers, J.F. Soriano, J. Souchard, R. Squartini, M. Stadelmaier, D. Stanca, S. Stanič, J. Stasielak, P. Stassi, M. Stolpovskiy, A. Streich, M. Suárez-Durán, T. Sudholz, T. Suomijä rvi, A.D. Supanitsky, J. Šupík, Z. Szadkowski, A. Taboada, O.A. Taborda, A. Tapia, C. Timmermans, P. Tobiska, C.J. Todero Peixoto, B. Tomé, G. Torralba Elipe, A. Travaini, P. Travnicek, M. Trini, M. Tueros, R. Ulrich, M. Unger, M. Urban, J.F. Valdés Galicia, I. Valiño, L. Valore, A.M. van den Berg, A. van Vliet, E. Varela, B. Vargas Cárdenas, A. Vásquez-Ramírez, D. Veberič, C. Ventura, I.D. Vergara

Quispe, V. Verzi, J. Vicha, L. Villaseñor, J. Vink, S. Vorobiov, H. Wahlberg, A.A. Watson, M. Weber, A. Weindl, M. Wiedeński, L. Wiencke, H. Wilczyński, T. Winchen, M. Wirtz, D. Wittkowski, B. Wundheiler, L. Yang, A. Yushkov, E. Zas, D. Zavrtanik, M. Zavrtanik, L. Zehrer, A. Zepeda, B. Zimmermann, M. Ziolkowski, F. Zuccarello. Proc. 36th ICRC PoS, 482, (2019). https://pos.sissa.it/358/482/pdf

[6] R.U. Abbasi, M. Abe, T. Abu-Zayyad, M. Allen, R. Azuma, E. Barcikowski, J.W. Belz, D.R. Bergman, S.A. Blake, R. Cady, B.G. Cheon, J. Chiba, M. Chikawa, A. di Matteo, T. Fujii, K. Fujita, M. Fukushima, G. Furlich, T. Goto, W. Hanlon, M. Hayashi, Y. Hayashi, N. Hayashida, K. Hibino, K. Honda, D. Ikeda, N. Inoue, T. Ishii, R. Ishimori, H. Ito, D. Ivanov, H.M. Jeong, S.M. Jeong, C.C. H. Jui, K. Kadota, F. Kakimoto, O. Kalashev, K. Kasahara, H. Kawai, S. Kawakami, S. Kawana, K. Kawata, E. Kido, H.B. Kim, J.H. Kim, J.H. Kim, S. Kishigami, S. Kitamura, Y. Kitamura, V. Kuzmin, M. Kuznetsov, Y.J. Kwon, K.H. Lee, B. Lubsandorzhiev, J.P. Lundquist, K. Machida, K. Martens, T. Matsuyama, J.N. Matthews, R. Mayta, M. Minamino, K. Mukai, I. Myers, K. Nagasawa, S. Nagataki, R. Nakamura, T. Nakamura, T. Nonaka, H. Oda, S. Ogio, J. Ogura, M. Ohnishi, H. Ohoka, T. Okuda, Y. Omura, M. Ono, R. Onogi, A. Oshima, S. Ozawa, I.H. Park, M.S. Pshirkov, D.C. Rodriguez, G. Rubtsov, D. Ryu, H. Sagawa, R. Sahara, K. Saito, Y. Saito, N. Sakaki, N. Sakurai, L.M. Scott, T. Seki, K. Sekino, P.D. Shah, F. Shibata, T. Shibata, H. Shimodaira, B.K. Shin, H.S. Shin, J.D. Smith, P. Sokolsky, B.T. Stokes, S.R. Stratton, T.A. Stroman, T. Suzawa, Y. Takagi, Y. Takahashi, M. Takamura, M.Takeda, R. Takeishi, A. Taketa, M. Takita, Y. Tameda, H. Tanaka, K. Tanaka, M. Tanaka, S.B. Thomas, G.B. Thomson, P. Tinyakov, I. Tkachev, H. Tokuno, T. Tomida, S. Troitsky, Y. Tsunesada, K. Tsutsumi, Y. Uchihori, S. Udo, F. Urban, T. Wong, M. Yamamoto, R. Yamane, H. Yamaoka, K. Yamazaki, J. Yang, K. Yashiro, Y. Yoneda, S. Yoshida, H. Yoshii, Y. Zhezher, Z. Zundel. Telescope Array Collaboration. Astrophys. J., **858**, 76 (2018). DOI: 10.3847/1538-4357/aabad7

[7] S. Ostapchenko. Phys. Rev. D, **83** (1), 1401 (2011). DOI: 10.1103/PhysRevD.83.01401

[8] L. Sveshnikova, I. Astapov, P. Bezyazykov, A. Blinov, E. Bonvech, A. Borodin, N. Budnev, A. Bulan, A. Vaidyanathan, N. Volkov, P. Volchugov, D. Voronin, A. Garmash, A. Gafarov, V. Grebenyuk, E. Gress, O. Gress, T. Gress, A. Grinyuk, O. Grishin, A. Dyachok, D. Zhurov, A. Zagorodnikov, A.L. Ivanova, M. Ilyushin, N. Kalmykov, V. Kindin, S. Kiryukhin, V. Kozhin, R. Kokoulin, N. Kolosov, K. Kompaniets, E. Korosteleva, E. Kravchenko, A. Kryukov, L. Kuzmichev, A. Chiavassa, M. Lavrova, A. Lagutin, Yu. Lemeshev, B. Lubsandorzhiev, N. Lubsandorzhiev, R. Mirgazov, R. Monkhoev, E. Okuneva, E. Osipova, A. Pan, A. Panov, L. Pankov, A. Pakhorukov, A. Petrukhin, D. Podgrudkov, E. Popova, E. Postnikov, V. Prosin, V. Ptuskin, A. Pushnin, A. Razumov, R. Raikin, G. Rubtsov, E. Ryabov, V. Samoliga, I. Satyshev, A. Sidorenkov, A. Silaev, A. Silaev Jr., A. Skurikhin, A. Sokolov, V. Tabolenko, A. Tanaev, M. Ternovoy, L. Tkachev, N. Ushakov, D. Chernov, D. Shipilov, I. Yashin. Phys. Atomic Nuclei, **86** (9), 1 (2023). DOI: 10.1134/S1063778823090247

[9] P.A. Volchugov, I.I. Astapov, P.A. Bezÿazykov, E.A. Bonvech, A.N. Borodin, N.M. Budnev, A.V. Bulan, A. Vaidyanatan, N.V. Volkov, D.M. Voronin, A.R. Gafarov, E.O. Gres', O.A. Gres', T.I. Gres', O.G. Grishin, A.Yu. Garmash, V.M. Grebenyuk, A.A. Grinyuk, A.N. Dyachok, D.P. Zhurov, A.V. Zagorodnikov, A.D. Ivanova, A.L. Ivanova, M.A. Ilyushin, N.N. Kalmykov, V.V. Kindin, S.N. Kiryukhin, R.P. Kokoulin, N.I. Kolosov, K.G. Kompaniets, E.E. Korosteleva, V.A. Kozhin, E.A. Kravchenko, A.P. Kryukov, L.A. Kuz'michev, A.K'yavassa, A.A. Lagutin, M.V. Lavrova, Yu.E. Lemeshev, B.K. Lubsandorzhiev, N.B. Lubsandorzhiev, S.D. Malakhov, R.R. Mirgazov, R.D. Monkhoev, E.A. Okuneva, E.A. Osipova, A.D. Panov, A.L. Pakhorukov, A. Pan, L.V. Pan'kov, A.A. Petrukhin, D.A. Podgrudkov, E.G. Popova, E.B. Postnikov, V.V. Prosin, V.S. Ptuskin, A.A. Pushnin, A.Yu. Razumov, R.I. Raikin, G.I. Rubtsov, E.V. Ryabov, V.S. Samoliga, I. Satyshev, L.G. Sveshnikova, A.A. Silaev, A. A. Silaev (Jr.), A.Yu. Sidorenkov, A.V. Skurikhin, A.V. Sokolov, V. A. Tabolenko, A.B. Tanaev, M.Yu. Ternovoi, L.G. Tkachev, N.A. Ushakov, D.V. Chernov, I.I. Yashin. Instruments and Experimental Techniques, **67**, 143 (2024). DOI: 10.1134/S0020441224700106

[10] P.A. Volchugov, E.A. Bonvech, A.V. Bulan, N.N. Kalmykov, E.E. Korosteleva, V.A. Kozhin, A.P. Kryukov, L.A. Kuz'michev, N.B. Lubsandorzhiev, E.A. Okuneva, E.A. Osipova, A.D. Panov, D.A. Podgrudkov, E.G. Popova, E.B. Postnikov, V.V. Prosin, A.Yu. Razumov, L.G. Sveshnikova, A.A. Silaev, A.A. Silaev (ml.), A.V. Skurikhin, D.V. Chernov, I.I. Astapov, V.V. Kindin, R.P. Kokoulin, K.G. Kompaniets, A.A. Petrukhin, I.I. Yashin, P.A. Bezyazykov, N.M. Budnev, A.R. Gafarov, O.A. Gres', T.I. Gres', E.O. Gres', O.G. Grishin, A.N. Dyachok, D.P. Zhurov, A.V. Zagorodnikov, A.L. Ivanova, A.D. Ivanova, M.A. Ilyushin, S.N. Kiryukhin, N.I. Kolosov, Yu.E. Lemeshev, S.D. Malakhov, R.R. Mirgazov, R.D. Monkhoev, L.V. Pan'kov, A.L. Pakhorukov, I.A. Poddubnyi, A.A. Pushnin, E.V. Ryabov, V.S. Samoliga, V.A. Tabolenko, A.B. Tanaev, M.Yu. Ternovoi, A.V. Blinov, A.N. Borodin, V.M. Grebenyuk, A.A. Grinyuk, M.V. Lavrova, A. Pan, I. Satyshev, A.V. Shaikovskii, D.M. Voronin, B.K. Lubsandorzhiev, A.D. Lukanov, G.I. Rubtsov, A.Yu. Sidorenkov, N.A. Ushakov, A.Yu. Garmash, E.A. Kravchenko, A.V. Sokolov, L.G. Tkachev, V.N. Zirakashvili, A. K'yavassa. EChAYa, **56**, 1062 (2025) (in Russian).

*Translated by M.Shevelev*