PROCEEDINGS OF SCIENCE

Searching for neutrino signals correlated with LHAASO diffuse Galactic emission

Wenlian Li,[a,*] **Tian-Qi Huang,**[b,c] **Donglian Xu**[a,d] **and Huihai He**[b,c,e] **for the LHAASO collaboration**

[a] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, 201210 Shanghai, China*

[b] *Key Laboratory of Particle Astrophysics & Experimental Physics Division & Computing Center, Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, China*

[c] *Tianfu Cosmic Ray Research Center, 610000 Chengdu, Sichuan, China*

[d] *School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MoE), Shanghai Key Laboratory for Particle Physics and Cosmology, 200240 Shanghai, China*

[e] *University of Chinese Academy of Sciences, 100049 Beijing, China*

E-mail: wenlianli@sjtu.edu.cn, huangtq@ihep.ac.cn

The diffuse Galactic γ-ray emission is produced from the interaction of cosmic rays and interstellar medium or radiation fields in the Galaxy, where neutrino production is also expected. Recently, the Large High Altitude Air Shower Observatory (LHAASO) reported the measurements of the diffuse γ-ray from the Galactic plane with energies above 10 TeV. In this study, we construct the neutrino emission template based on LHAASO's observation and search for diffuse neutrinos accompanying the LHAASO diffuse Galactic γ-ray emission using ten-year IceCube track events. No significant signals are found. We set 90% confidence level upper limits, resulting in the neutrino flux of $\mathrm{d}\phi_\nu/\mathrm{dE}_\nu = 1.27 \times 10^{-14}(\mathrm{E}_\nu/25\mathrm{TeV})^{-2.99}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the diffuse γ-ray flux map with a 1.5σ significance cut.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

1. Introduction

The origin and acceleration mechanism of the high-energy cosmic rays remain a puzzle since the discovery of cosmic rays in 1912 [1]. During the propagation within the Galactic plane, cosmic rays interact with the dense interstellar medium through deep inelastic scattering, producing multiple secondary particles. Among these particles, neutral pions (π^0) decay into γ-rays, while charged pions ($\pi^{\pm}$) decay into neutrinos. These electrically neutral particles can point back to the origin. Thus, the Galactic plane serves as an ideal "cloud chamber" for tracing these high-energy cosmic rays.

The diffuse Galactic γ-ray emission (DGE) from the Galactic plane has been measured by many experiments from sub-GeV to PeV [2–8]. The DGE primarily originates from the decay of neutral pions, bremsstrahlung radiation, and the inverse Compton scattering. The hadronic (π^0-decay) component tends to be dominant at higher energies in some theoretical models [e.g., 9, 10]. We expect to detect the diffuse Galactic neutrinos that are produced with these π^0-decay γ-rays.

In the decade, IceCube and ANTARES have conducted many searches for Galactic neutrinos using different data samples, including the high-energy starting events (HESE) [11], through-going track events [12–15], and cascade events [13, 16]. All the searches have shown that the correlation between the neutrinos and the Galactic plane is not clear, and the diffuse Galactic neutrino emission is not significant. Recently, strong evidence (4.5σ) of neutrino emission from the Galactic plane has been confirmed by IceCube with 10 years cascade data [17]. Model-dependent templates, such as the Fermi-LAT π^0-decay model [2] and the KRA$_\gamma$ model [9], are widely used in the searches above. These templates provide prior distributions of neutrino signals in both spatial and energy domains. With the public IceCube data, an anisotropic component of neutrino flux was found in the direction of low Galactic latitudes with the significance of $\gtrsim 3\sigma$ [18] and 4.1σ[19]. The latter study also estimated the flux of Galactic neutrinos but didn't consider the instrument response to signal and background events in detail. Additionally, ANTARES found a hint for a TeV neutrino emission from the Galactic Ridge [20].

In this contribution, we use the ten-year IceCube muon-track data to conduct a template search for diffuse Galactic neutrinos originating from the Galactic plane and try to constrain the upper limit on the hadronic contribution to the observed DGE. The ten-year muon-track data used in our study is larger in scale compared to the data samples used in previous searches [12–15], and it has been publicly released [21]. Additionally, IceCube has released the corresponding instrument response functions, which enable the conversion of signal events into neutrino flux. The precise measurement of DGE from 10 TeV to PeV by LHAASO provides a brand new template for diffuse Galactic neutrino emission. Moreover, it represents the first measurement of DGE from the outer Galactic plane [8].

2. LHAASO & IceCube Synergy

The IceCube Neutrino Observatory [22] is a Cherenkov detector array locating at the South Pole. IceCube consists of 86 strings installed between 1.45 and 2.45 km deep in the ice. The 5160 digital optical modules (DOMs) in total, instrumenting 1km^3 ice, are able to detect the Cherenkov radiation produced by the secondary charged particles induced from the deep inelastic scattering interactions of high-energy muon neutrinos and ice. In this scenario, the detector records a track-like morphology, which is referred to as a track event. IceCube has a field of view (FOV) that covers the entire sky. However, the track data are primarily sensitive to the northern hemisphere since atmospheric muons are shielded by the Earth.

The Large High Altitude Air Shower Observatory (LHAASO), located at an altitude of 4410 m above sea level in Daocheng, Sichuan Province, China, is a mega-scale composite instrument designed to study γ-rays and cosmic rays [23]. The Kilometer Square Array (KM2A) of LHAASO, which comprises 5216 electromagnetic particle detectors and 1188 muon detectors covering an area of ~ 1.3 km^2, is optimized for detecting γ-rays with energies ranging from 10 TeV to a few PeV [24]. Located at a latitude of $\sim 29°$ North, LHAASO has a wide FOV spanning from a declination of $-21°$ to $79°$.

It's adequate to conduct neutrino and γ-ray joint searches with IceCube and LHAASO instruments for multiple reasons. Firstly, both LHAASO and IceCube are sensitive to the northern sky. Secondly, the broad energy band coverage of LHAASO, extending up to the PeV range, overlaps with that of IceCube, enabling the search for high-energy γ-rays and neutrinos produced by the hadronic interactions of high-energy cosmic rays.

3. Gamma-ray and Neutrino Datasets

Recently, LHAASO-KM2A measured diffuse γ-rays from the Galactic plane with energies from 10 TeV to 1 PeV [8]. All known point-like and extended sources detected by KM2A as well as those from TeVCat are masked in the measurement of DGE. The observations are conducted in two regions: the inner Galaxy region ($15° < l < 125°$, $|b| < 5°$) and the outer Galaxy region ($125° < l < 235°$, $|b| < 5°$). The spectrum of the diffuse emission are fitted with a power-law function $\mathrm{d}\phi/\mathrm{d}E = \phi_0(E/50\ \mathrm{TeV})^{-\gamma}$, characterized by a spectral index of $\gamma = 2.99$.

In this study, we use the diffuse γ-rays flux map of the Galactic plane ($15° < l < 235°$, $|b| < 5°$) observed by LHAASO-KM2A as the neutrino spatial template, with all point-like and extended sources on the flux map masked. To reduce the influence of the background fluctuations, we implement significance cuts to the flux map. Flux maps with 0.5σ, 1σ, 1.5σ, and 2σ cuts are tested. Additionally, we test a uniform map, as well as a gas template traced by the PLANK dust opacity map assuming the gas column density is proportional to the opacity [25], in the same region ($15° < l < 235°$, $|b| < 5°$) for comparison purposes.

For the neutrino data, the public ten-year IceCube track data [21], including the experimental data events, instrument response functions, and detector uptime are used in this study.

4. Analysis Method

Since the emission from the Galactic plane is quite extensive and exhibits diffuse morphology, the unbinned maximum likelihood commonly used in neutrino point-source searches [26] is not suitable for this analysis. Instead, we use the ps-template likelihood, as illustrated in [12], to search for neutrino emission from the Galactic plane. The signal-subtracted template likelihood [27] is defined as:

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i(\mathbf{x}_i, \sigma_i, E_i; \gamma) + \widetilde{D}_i(sin\delta_i, E_i) - \frac{n_s}{N} \widetilde{S}_i(sin\delta_i, E_i) \right) \tag{1}$$

where n_s is number of signal events, N is the total number of events, S_i is the signal probability density function (PDF), $\widetilde{D}_i$ is the scrambled background PDF estimated from data, and $\widetilde{S}_i$ is the scrambled signal PDF. Each PDF comprises a spatial term and an energy term. The details of the construction of the likelihood follow the methods described in [12, 28, 29]. In the maximization of the likelihood, we only fit the number of signal events $\hat{n}_s$ and the spectral index is fixed as $\gamma = 2.99$, which is derived from the measurement of LHAASO. Since most of the neutrino events correspond to γ-rays below 100 TeV, the γ-ray absorption due to the interstellar radiation field have little effect on our results [30]. The test statistic, which is defined as the log-likelihood ratio $TS = -2\ln(L(n_s = 0)/L(\hat{n}_s, \gamma))$, is used to derive the significance and upper limits.

5. Summary and Discussion

The results for Galactic plane template searches are summarized in Table 1 and Table 2. Although some excesses from the LHAASO diffuse Galactic γ-ray emission are observed, the results are not statistically significant. We set 90% confidence level (C.L.) upper limits on the muon neutrino flux. Figure 1 shows the 90% C.L. moun neutrino upper limit flux obtained in the template searches, in comparison to the theoretically predicted muon neutrino flux derived from the LHAASO diffuse Galactic γ-ray observation assuming hadronuclear interactions. With different cuts on the significance, the resulting upper limits are 1.2 to 2.2 times higher than the theoretical prediction if all the γ-rays are of hadronic origin. The p-values obtained from the flux templates are lower than those from the uniform and gas templates, suggesting that the flux templates likely provide a better description of the true spatial distribution of neutrino signals.

Spatial Template	$\hat{n}_s$	Upper Limit $\phi_{90\%}$	$\phi_{90\%}^{\text{observed}}/\phi^{\text{theoretical}}$	Pretrial p-value
Flux map (0.5σ)	233.8	1.17×10^{-14}	123.9%	0.076
Flux map (1.0σ)	257.2	1.22×10^{-14}	146.9%	0.058
Flux map (1.5σ)	285.2	1.27×10^{-14}	186.0%	0.038
Flux map (2.0σ)	239.2	1.08×10^{-14}	217.5%	0.044

Table 1: Results of template searches. The spatial template, the best fit number of signal events $\hat{n}_s$, the 90% C.L. upper limit flux parameterized as $\mathrm{d}\phi_{\nu_\mu+\bar{\nu}_\mu}/\mathrm{d}E_\nu = \phi_{90\%} \cdot (E_\nu/25\ \mathrm{TeV})^{-2.99}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for the power-law neutrino spectrum converted from the γ-ray spectrum, and a percentage of the observed upper limit on muon neutrino flux relative to the theoretically predicted muon neutrino flux are listed, with the last column shows the pretrial p-value of each search.

In the following research, we will use the neutrino emission templates based on observations by the Water Cherenkov Detector Array (WCDA) of LHAASO. WCDA operates in the energy range from 100 GeV to 10 TeV, with the corresponding neutrino energy below 5 TeV. Some models predict that the hadronic emission is more dominant in the lower energy range [31].

Spatial Template	$\hat{n}_s$	Upper Limit $\phi_{90\%}$	Pretrial p-value
Uniform map (with mask)	131.9	1.01×10^{-14}	0.226
Gas template (with mask)	184.1	1.12×10^{-14}	0.155
Gas template	244.3	1.25×10^{-14}	0.085

Table 2: Results of template searches. Same as Table 1 but for testing the uniform map and gas template. The first two rows correspond to the uniform and gas templates with a mask, indicating that all regions with point-like and extended sources are masked. The last row represents the use of the gas template without a mask.

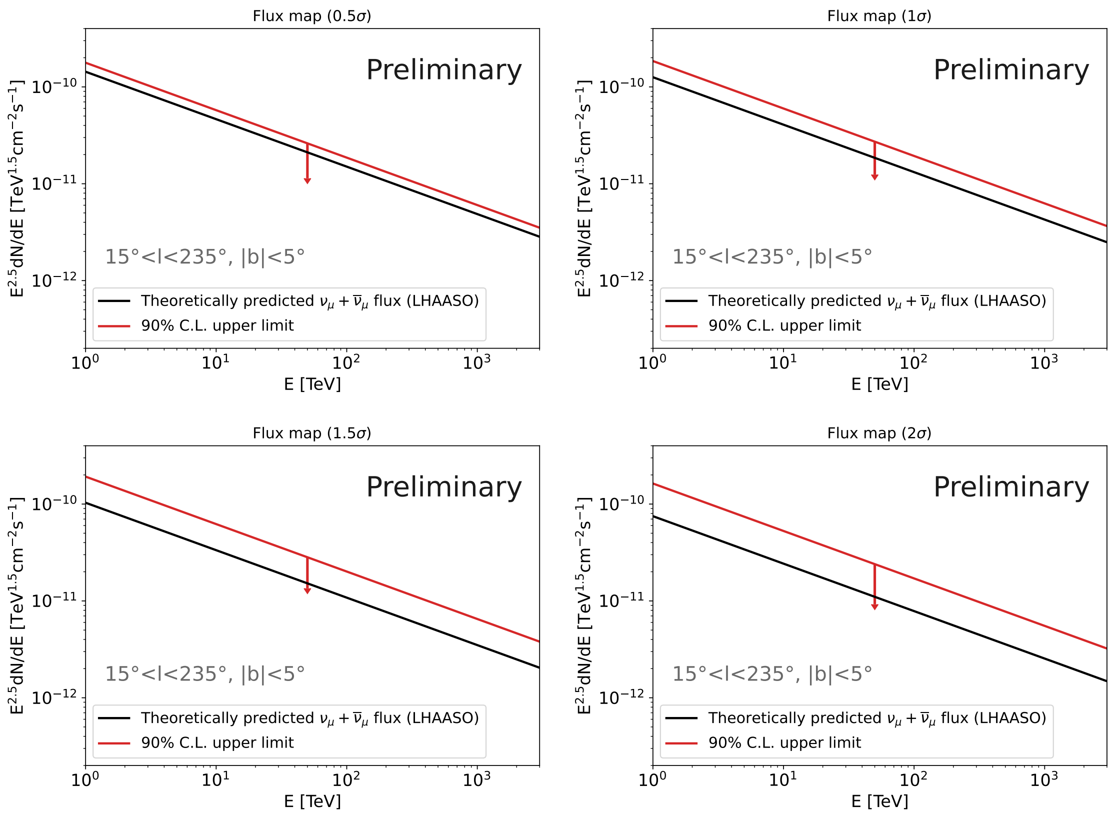

Figure 1: Upper limits (90% C.L.) on the muon neutrino flux (red) for the template searches of LHAASO diffuse Galactic γ-ray flux maps with different significance cut. The theoretically predicted muon neutrino flux derived from the LHAASO γ-ray observation assuming hadronuclear interactions is shown in black.

References

[1] V.F. Hess, *Observations in low level radiation during seven free balloon flights*, *Phys. Zeit* **13** (1912) 1084.

[2] Fermi-LAT collaboration, *Fermi-LAT Observations of the Diffuse Gamma-Ray Emission: Implications for Cosmic Rays and the Interstellar Medium*, *Astrophys. J.* **750** (2012) 3 [1202.4039].

[3] A.A. Abdo, B. Allen, T. Aune, D. Berley, E. Blaufuss, S. Casanova et al., *A Measurement of the Spatial Distribution of Diffuse TeV Gamma-Ray Emission from the Galactic Plane with Milagro*, *Astrophys. J.* **688** (2008) 1078 [0805.0417].

[4] A. Abramowski, F. Aharonian, F. Ait Benkhali, A.G. Akhperjanian, E.O. Angüner, M. Backes et al., *Diffuse Galactic gamma-ray emission with H.E.S.S.*, *Phys. Rev. D* **90** (2014) 122007 [1411.7568].

[5] B. Bartoli, P. Bernardini, X.J. Bi, P. Branchini, A. Budano, P. Camarri et al., *Study of the Diffuse Gamma-Ray Emission from the Galactic Plane with ARGO-YBJ*, *Astrophys. J.* **806** (2015) 20 [1507.06758].

[6] Tibet ASgamma collaboration, *First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies*, *Phys. Rev. Lett.* **126** (2021) 141101 [2104.05181].

[7] HAWC collaboration, *Galactic Gamma-Ray Diffuse Emission at TeV energies with HAWC Data*, in *37th International Cosmic Ray Conference*, p. 835, Mar., 2022, DOI.

[8] LHAASO collaboration, *Measurement of ultra-high-energy diffuse gamma-ray emission of the Galactic plane from 10 TeV to 1 PeV with LHAASO-KM2A*, 2305.05372.

[9] D. Gaggero, D. Grasso, A. Marinelli, A. Urbano and M. Valli, *The gamma-ray and neutrino sky: A consistent picture of Fermi-LAT, Milagro, and IceCube results*, *Astrophys. J. Lett.* **815** (2015) L25 [1504.00227].

[10] P. Lipari and S. Vernetto, *Diffuse Galactic gamma ray flux at very high energy*, *Phys. Rev. D* **98** (2018) 043003 [1804.10116].

[11] IceCube collaboration, *Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data*, *Phys. Rev. Lett.* **113** (2014) 101101 [1405.5303].

[12] IceCube collaboration, *Constraints on Galactic Neutrino Emission with Seven Years of IceCube Data*, *Astrophys. J.* **849** (2017) 67 [1707.03416].

[13] ANTARES collaboration, *New constraints on all flavor Galactic diffuse neutrino emission with the ANTARES telescope*, *Phys. Rev. D* **96** (2017) 062001 [1705.00497].

[14] ANTARES, IceCube collaboration, *Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes*, *Astrophys. J. Lett.* **868** (2018) L20 [1808.03531].

[15] IceCube, HAWC collaboration, *IceCube Search for Galactic Neutrino Sources based on HAWC Observations of the Galactic Plane*, *PoS* **ICRC2019** (2020) 932 [1908.08546].

[16] IceCube collaboration, *Search for Sources of Astrophysical Neutrinos Using Seven Years of IceCube Cascade Events*, *Astrophys. J.* **886** (2019) 12 [1907.06714].

PoS(ICRC2023)1091

[17] R. Abbasi et al., *Observation of high-energy neutrinos from the Galactic plane*, *Science* **380** (2023) 6652 [2307.04427].

[18] A. Neronov and D.V. Semikoz, *Evidence the Galactic contribution to the IceCube astrophysical neutrino flux*, *Astropart. Phys.* **75** (2016) 60 [1509.03522].

[19] Y.Y. Kovalev, A.V. Plavin and S.V. Troitsky, *Galactic Contribution to the High-energy Neutrino Flux Found in Track-like IceCube Events*, *Astrophys. J. Lett.* **940** (2022) L41 [2208.08423].

[20] ANTARES collaboration, *Hint for a TeV neutrino emission from the Galactic Ridge with ANTARES*, *Phys. Lett. B* **841** (2023) 137951 [2212.11876].

[21] IceCube Collaboration, R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *IceCube Data for Neutrino Point-Source Searches Years 2008-2018*, *arXiv e-prints* (2021) arXiv:2101.09836 [2101.09836].

[22] IceCube collaboration, *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, *JINST* **12** (2017) P03012 [1612.05093].

[23] Z. Cao, D. della Volpe, S. Liu, Editors, :, X. Bi et al., *The Large High Altitude Air Shower Observatory (LHAASO) Science Book (2021 Edition)*, *arXiv e-prints* (2019) arXiv:1905.02773 [1905.02773].

[24] LHAASO collaboration, *Design of the lhaaso detectors*, *Radiation Detection Technology and Methods* **2** (2018) 7.

[25] Planck collaboration, *Planck intermediate results. XLVIII. Disentangling Galactic dust emission and cosmic infrared background anisotropies*, *Astron. Astrophys.* **596** (2016) A109 [1605.09387].

[26] J. Braun, J. Dumm, F. De Palma, C. Finley, A. Karle and T. Montaruli, *Methods for point source analysis in high energy neutrino telescopes*, *Astroparticle Physics* **29** (2008) 299.

[27] IceCube collaboration, *Search for extended sources of neutrino emission with 7 years of IceCube data*, *PoS* **ICRC2017** (2018) 963.

[28] E. Pinat, *The IceCube Neutrino Observatory: search for extended sources of neutrinos and preliminary study of a communication protocol for its future upgrade*, Ph.D. thesis, Brussels U., 2017.

[29] T.-Q. Huang and Z. Li, *Neutrino observations of LHAASO sources: Present constraints and future prospects*, *Mon. Notices Royal Astron. Soc.* **514** (2022) 852 [2112.14062].

[30] S. Vernetto and P. Lipari, *Absorption of very high energy gamma rays in the Milky Way*, *Phys. Rev. D* **94** (2016) 063009 [1608.01587].

[31] P.D. Marinos, G.P. Rowell, T.A. Porter and G. Jóhannesson, *The steady-state multi-TeV diffuse γ-ray emission predicted with galprop and prospects for the Cherenkov Telescope Array*, *Mon. Not. Roy. Astron. Soc.* **518** (2022) 5036 [2211.01619].

Full Authors List: LHAASO Collaboration

Zhen Cao[1,2,3], F. Aharonian[4,5], Q. An[6,7], Axikegu[8], Y.X. Bai[1,3], Y.W. Bao[9], D. Bastieri[10], X.J. Bi[1,2,3], Y.J. Bi[1,3], J.T. Cai[10], Q. Cao[11], W.Y. Cao[7], Zhe Cao[6,7], J. Chang[12], J.F. Chang[1,3,6], A.M. Chen[13], E.S. Chen[1,2,3], Liang Chen[14], Lin Chen[8], Long Chen[8], M.J. Chen[1,3], M.L. Chen[1,3,6], Q.H. Chen[8], S.H. Chen[1,2,3], S.Z. Chen[1,3], T.L. Chen[15], Y. Chen[9], N. Cheng[1,3], Y.D. Cheng[1,3], M.Y. Cui[12], S.W. Cui[11], X.H. Cui[16], Y.D. Cui[17], B.Z. Dai[18], H.L. Dai[1,3,6], Z.G. Dai[7], Danzengluobu[15], D. della Volpe[19], X.Q. Dong[1,2,3], K.K. Duan[12], J.H. Fan[10], Y.Z. Fan[12], J. Fang[18], K. Fang[1,3], C.F. Feng[20], L. Feng[12], S.H. Feng[1,3], X.T. Feng[20], Y.L. Feng[15], S. Gabici[21], B. Gao[1,3], C.D. Gao[20], L.Q. Gao[1,2,3], Q. Gao[15], W. Gao[1,3], W.K. Gao[1,2,3], M.M. Ge[18], L.S. Geng[1,3], G. Giacinti[13], G.H. Gong[22], Q.B. Gou[1,3], M.H. Gu[1,3,6], F.L. Guo[14], X.L. Guo[8], Y.Q. Guo[1,3], Y.Y. Guo[12], Y.A. Han[23], H.H. He[1,2,3], H.N. He[12], J.Y. He[12], X.B. He[17], Y. He[8], M. Heller[19], Y.K. Hor[17], B.W. Hou[1,2,3], C. Hou[1,3], X. Hou[24], H.B. Hu[1,2,3], Q. Hu[7,12], S.C. Hu[1,2,3], D.H. Huang[8], T.Q. Huang[1,3], W.J. Huang[17], X.T. Huang[20], X.Y. Huang[12], Y. Huang[1,2,3], Z.C. Huang[8], X.L. Ji[1,3,6], H.Y. Jia[8], K. Jia[20], K. Jiang[6,7], X.W. Jiang[1,3], Z.J. Jiang[18], M. Jin[8], M.M. Kang[25], T. Ke[1,3], D. Kuleshov[26], K. Kurinov[26], B.B. Li[11], Cheng Li[6,7], Cong Li[1,3], D. Li[1,2,3], F. Li[1,3,6], H.B. Li[1,3], H.C. Li[1,3], H.Y. Li[7,12], J. Li[7,12], Jian Li[7], Jie Li[1,3,6], K. Li[1,3], W.L. Li[20], W.L. Li[13], X.R. Li[1,3], Xin Li[6,7], Y.Z. Li[1,2,3], Zhe Li[1,3], Zhuo Li[27], E.W. Liang[28], Y.F. Liang[28], S.J. Lin[17], B. Liu[7], C. Liu[1,3], D. Liu[20], H. Liu[8], H.D. Liu[23], J. Liu[1,3], J.L. Liu[1,3], J.Y. Liu[1,3], M.Y. Liu[15], R.Y. Liu[9], S.M. Liu[8], W. Liu[1,3], Y. Liu[10], Y.N. Liu[22], R. Lu[18], Q. Luo[17], H.K. Lv[1,3], B.Q. Ma[27], L.L. Ma[1,3], X.H. Ma[1,3], J.R. Mao[24], Z. Min[1,3], W. Mitthumsiri[29], H.J. Mu[23], Y.C. Nan[1,3], A. Neronov[21], Z.W. Ou[17], B.Y. Pang[8], P. Pattarakijwanich[29], Z.Y. Pei[10], M.Y. Qi[1,3], Y.Q. Qi[11], B.Q. Qiao[1,3], J.J. Qin[7], D. Ruffolo[29], A. Sáiz[29], D. Semikoz[21], C.Y. Shao[17], L. Shao[11], O. Shchegolev[26,30], X.D. Sheng[1,3], F.W. Shu[31], H.C. Song[27], Yu.V. Stenkin[26,30], V. Stepanov[26], Y. Su[12], Q.N. Sun[8], X.N. Sun[28], Z.B. Sun[32], P.H.T. Tam[17], Q.W. Tang[31], Z.B. Tang[6,7], W.W. Tian[2,16], C. Wang[32], C.B. Wang[8], G.W. Wang[7], H.G. Wang[10], H.H. Wang[17], J.C. Wang[24], K. Wang[9], L.P. Wang[20], L.Y. Wang[1,3], P.H. Wang[8], R. Wang[20], W. Wang[17], X.G. Wang[28], X.Y. Wang[9], Y. Wang[8], Y.D. Wang[1,3], Y.J. Wang[1,3], Z.H. Wang[25], Z.X. Wang[18], Zhen Wang[13], Zheng Wang[1,3,6], D.M. Wei[12], J.J. Wei[12], Y.J. Wei[1,2,3], T. Wen[18], C.Y. Wu[1,3], H.R. Wu[1,3], S. Wu[1,3], X.F. Wu[12], Y.S. Wu[7], S.Q. Xi[1,3], J. Xia[7,12], J.J. Xia[8], G.M. Xiang[2,14], D.X. Xiao[11], G. Xiao[1,3], G.G. Xin[1,3], Y.L. Xin[8], Y. Xing[14], Z. Xiong[1,2,3], D.L. Xu[13], R.F. Xu[1,2,3], R.X. Xu[27], W.L. Xu[25], L. Xue[20], D.H. Yan[18], J.Z. Yan[12], T. Yan[1,3], C.W. Yang[25], F. Yang[11], F.F. Yang[1,3,6], H.W. Yang[17], J.Y. Yang[17], L.L. Yang[17], M.J. Yang[1,3], R.Z. Yang[7], S.B. Yang[18], Y.H. Yao[25], Z.G. Yao[1,3], Y.M. Ye[22], L.Q. Yin[1,3], N. Yin[20], X.H. You[1,3], Z.Y. You[1,3], Y.H. Yu[7], Q. Yuan[12], H. Yue[1,2,3], H.D. Zeng[12], T.X. Zeng[1,3,6], W. Zeng[18], M. Zha[1,3], B.B. Zhang[9], F. Zhang[8], H.M. Zhang[9], H.Y. Zhang[1,3], J.L. Zhang[16], L.X. Zhang[10], Li Zhang[18], P.F. Zhang[18], P.P. Zhang[7,12], R. Zhang[7,12], S.B. Zhang[2,16], S.R. Zhang[11], S.S. Zhang[1,3], X. Zhang[9], X.P. Zhang[1,3], Y.F. Zhang[8], Yi Zhang[1,12], Yong Zhang[1,3], B. Zhao[8], J. Zhao[1,3], L. Zhao[6,7], L.Z. Zhao[11], S.P. Zhao[12,20], F. Zheng[32], B. Zhou[1,3], H. Zhou[13], J.N. Zhou[14], M. Zhou[31], P. Zhou[9], R. Zhou[25], X.X. Zhou[8], C.G. Zhu[20], F.R. Zhu[8], H. Zhu[16], K.J. Zhu[1,2,3,6] and X. Zuo[1,3]

[1]Key Laboratory of Particle Astrophyics & Experimental Physics Division & Computing Center, Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, China. [2]University of Chinese Academy of Sciences, 100049 Beijing, China. [3]Tianfu Cosmic Ray Research Center, 610000 Chengdu, Sichuan, China. [4]Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, 2 Dublin, Ireland . [5]Max-Planck-Institut for Nuclear Physics, P.O. Box 103980, 69029 Heidelberg, Germany. [6]State Key Laboratory of Particle Detection and Electronics, China. [7]University of Science and Technology of China, 230026 Hefei, Anhui, China. [8]School of Physical Science and Technology & School of Information Science and Technology, Southwest Jiaotong University, 610031 Chengdu, Sichuan, China. [9]School of Astronomy and Space Science, Nanjing University, 210023 Nanjing, Jiangsu, China. [10]Center for Astrophysics, Guangzhou University, 510006 Guangzhou, Guangdong, China. [11]Hebei Normal University, 050024 Shijiazhuang, Hebei, China. [12]Key Laboratory of Dark Matter and Space Astronomy & Key Laboratory of Radio Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, 210023 Nanjing, Jiangsu, China. [13]Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University, 200240 Shanghai, China. [14]Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 200030 Shanghai, China. [15]Key Laboratory of Cosmic Rays (Tibet University), Ministry of Education, 850000 Lhasa, Tibet, China. [16]National Astronomical Observatories, Chinese Academy of Sciences, 100101 Beijing, China. [17]School of Physics and Astronomy (Zhuhai) & School of Physics (Guangzhou) & Sino-French Institute of Nuclear Engineering and Technology (Zhuhai), Sun Yat-sen University, 519000 Zhuhai & 510275 Guangzhou, Guangdong, China. [18]School of Physics and Astronomy, Yunnan University, 650091 Kunming, Yunnan, China. [19]Département de Physique Nucléaire et Corpusculaire, Faculté de Sciences, Université de Genève, 24 Quai Ernest Ansermet, 1211 Geneva, Switzerland. [20]Institute of Frontier and Interdisciplinary Science, Shandong University, 266237 Qingdao, Shandong, China. [21]APC, Université Paris Cité, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, 119 75205 Paris, France. [22]Department of Engineering Physics, Tsinghua University, 100084 Beijing, China. [23]School of Physics and Microelectronics, Zhengzhou University, 450001 Zhengzhou, Henan, China. [24]Yunnan Observatories, Chinese Academy of Sciences, 650216 Kunming, Yunnan, China. [25]College of Physics, Sichuan University, 610065 Chengdu, Sichuan, China. [26]Institute for Nuclear Research of Russian Academy of Sciences, 117312 Moscow, Russia. [27]School of Physics, Peking University, 100871 Beijing, China. [28]School of Physical Science and Technology, Guangxi University, 530004 Nanning, Guangxi, China. [29]Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand. [30]Moscow Institute of Physics and Technology, 141700 Moscow, Russia. [31]Center for Relativistic Astrophysics and High Energy Physics, School of Physics and Materials Science & Institute of Space Science and Technology, Nanchang University, 330031 Nanchang, Jiangxi, China. [32]National Space Science Center, Chinese Academy of Sciences, 100190 Beijing, China.