PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Observation of Horizontal Air Showers with LHAASO-KM2A

Quanbu Gou,[a,b,c,*] **Zhuo Li,**[d] **Di Sciascio Giuseppe,**[e] **Chao Hou,**[a,b,c] **Jiangtao Liu,**[a] **Xiaochuan Chang,**[a] **Hongkui Lv,**[a,b] **Lili Yang,**[f] **Sujie Lin,**[f] **Andrea Addazi,**[g] **Xuewen Liu,**[g] **Mingming Kang,**[g] **Antonino Marciano,**[h] **Jinsheng Gou,**[i] **Shiyu Yin,**[j] **Yaping Wang,**[a,b,c] **Zihan Yang,**[a,b,c] **Xishui Tian,**[d] **Qinyuan Zhang,**[d] **Silvia Miozzi,**[e] **Chengyu Shao,**[f] **Jie Dou,**[g] **Xuwei Ou,**[g] **Yukun Xue,**[g] **Lingyi Fu,**[g] **Qianxun Zuo,**[g] **Zhiheng Wang,**[g] **Yuanqing Wang,**[g] **Chenyang Gong,**[g] **Zhibo Yu,**[h] **Jiaming Li,**[h] **Qunfeng Jiang**[h] **and Lin Liu**[j]

[a] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences 100049 Beijing, China*
[b] *TIANFU Cosmic Ray Research Center, 610065 Chengdu, Sichuan, China*
[c] *University of Chinese Academy of Sciences, 100049 Beijing, China*
[d] *Department of Astronomy, School of Physics, Peking University, 100871 Beijing, China*
[e] *INFN - Roma Tor Vergata, Via della Ricerca Scientifica 1, Rome, Italy*
[f] *School of Physics and Astronomy, Sun Yat-sen University, 519000 Zhuhai, Guangdong, China*
[g] *College of Physics, Sichuan University, 610065 Chengdu, Sichuan, China*
[h] *Department of Physics, Fudan University, 200438 Shanghai, China*
[i] *College of Materials Science and Technology, Beijing Forestry University, 100083 Beijing, China*
[j] *School of Mechanical and Material Engineering, North China University of Technology, 100144 Beijing, China*

E-mail: giuseppe.disciascio@roma2.infn.it, zhuo.li@pku.edu.cn, gouqb@ihep.ac.cn

LHAASO-KM2A is a sub-array of the Large High Altitude Air Shower Observatory (LHAASO) with an area of kilometer squared scale, consisting of 5195 electromagnetic detectors and 1171 muon detectors. Horizontal Air Showers (HAS) are a fundamental tool to detect penetrating particles like neutrinos and to study hadronic interactions. HAS detected at the ground are mainly constituted by secondary muons. In this contribution first observations of HAS with half array of LHAASO-KM2A are reported. We show that the zenith angle distribution of extensive air showers (EAS) and the transition from electromagnetic-dominated showers to muon-dominated ones above a zenith angle of 60°.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

1. Introduction

The detection by LHAASO in the Northern hemisphere of some gamma ray sources emitting radiation well beyond 500 TeV opened the PeV sky to observations [1]. Some of these Ultra-High Energy (UHE) emissions are probably due to hadronic mechanisms producing at the same time photons and neutrinos through the decay of charged pions in *p*-*p* interactions. Leptonic mechanisms can hardly produce UHE gamma rays. The observation of neutrinos is the *smoking gun* to identify the hadronic nature of the emission.

Neutrinos can be detected by air shower arrays through the observation of Horizontal Air Showers (HAS), showers coming from zenith angles greater than 60°. The observation of extensive air showers in nearly horizontal directions provides a *"well-shielded laboratory"* for the detection of penetrating particles: high energy muons, cosmic neutrinos, possible weakly interacting particles produced in the decays of cosmological superheavy particles, will leave a clear signature in this dump.

The cosmic ray (CR) flux is a steeply falling function of zenith angle because the depth of atmosphere traversed by a shower reaching the ground rises rapidly from 1030 to about 36000 g/cm^2 as the zenith angle varies from zero to 90°. Thus near the horizon, the interaction point is separated by about 1000 radiation lengths of matter from the detector. Most secondaries such as electrons, pions and kaons are absorbed in the dump and only penetrating particles, such as muons and neutrinos produced in the initial interaction, can reach the detector. Therefore, to CRs incident near the horizon, the Earth's atmosphere represents a beam dump [2–4].

HAS are believed to be mainly due to the atmospheric muons and their interactions, as example:

(a) High energy single muons can interact through bremsstrahlung or deep inelastic scattering and initiate showers at the depth appropriate for detection. These showers are essentially electromagnetic, since the remnant muons from the initial shower (whose typical primary energy is not much larger than the muon one) are dispersed over a very large area.

(b) UHE CRs interacting at the top of the atmosphere, at very large zenith angles, produce a "large" amount of muons through the pion decays (favored, at large angles, with respect to pion interactions due to the low atmospheric density at the interaction altitude). Such showers are therefore composed essentially of muons since the e.m. component is completely absorbed.

Neutrino-induced showers have some intermediate typology, being more similar to conventional CR air showers or to events (a), when a large amount of their energy is transferred to the electromagnetic cascade. EAS arrays must have the possibility of discriminating between the different typologies of events through μ/e identification. Therefore, HAS is a possible tool for UHE cosmic neutrinos measurement.

The main experimental requirements for such studies are a good angular resolution to reject the background provided by mis-reconstructed conventional CR showers at smaller zenith angles and a very good muon identification capability.

In addition, measurements of the CRs rate at different zenith angles give information on the relative number of muons in a shower, which is dependent on the CR elemental composition, thus providing an important tool to probe the CR mass distribution and the hadronic interactions. For very high energy interactions the decay of charm particles is the dominant source of high-energy secondary muons. So counting high energy muons at large zenith angles determines the charm cross section. There is no background from the semi-leptonic decay of pions and kaons which, as a result of time dilation, interact and lose energy rather than decay into high energy muons.

The KM2A of the LHAASO experiment is well suited for this analysis due to its excellent muon identification capability thanks to the 40,000 m^2 muon detector total sensitive area. In this paper, a preliminary analysis of EAS reconstructed by using LHAASO-KM2A half-array data, from December 2019 to November 2020, with zenith angle greater than 60° is reported.

2. The KM2A array of LHAASO experiment

The KM2A array deploys over an area of 1.3 km^2 with 5195 electromagnetic detectors (EDs, 1 m^2 each) and 1188 muon detectors (MDs, 36 m^2 each), as shown in Fig.1. Within 575 m of the center of the array, EDs are distributed with a spacing of 15 m, and MDs of 30 m. Within the outskirt ring region, EDs are used to veto showers with cores located 60 m outside the central 1 km^2, its spacing is enlarged to 30 m.

For a typical ED, the detection efficiency for minimum ionization particles is about 98%. The time resolution is about 2 ns. The charge resolution is < 25% for a single particle. The dynamic range is from 1 to 10^4 particles. The average single rate is about 1.7 kHz with a threshold equivalent to 1/3 particle.

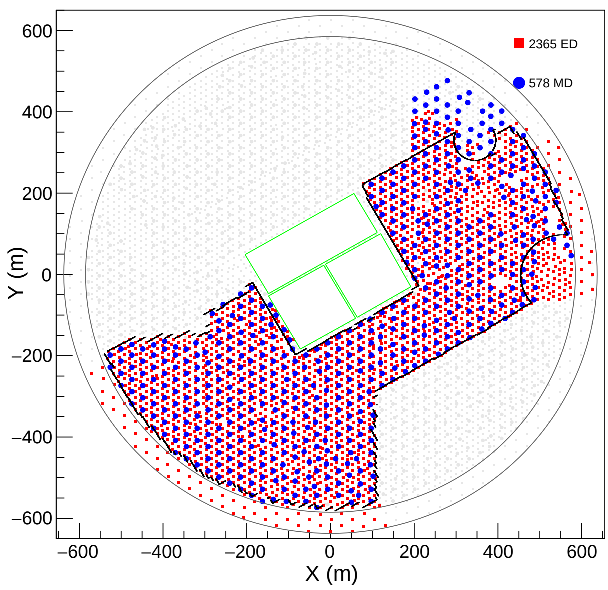


Figure 1: Planned layout of all LHAASO-KM2A detectors. The red squares and blue circles indicate the EDs and MDs in operation, respectively. The area enclosed by the dotted black line outlines the fiducial area of the current KM2A half-array used in this analysis. The central green squares indicate the LHAASO-WCDA array region.

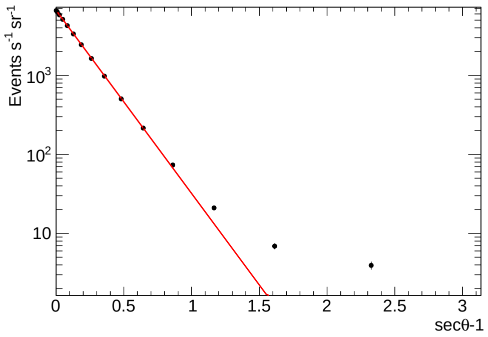


Figure 2: The zenith angle distribution of EAS measured with LHAASO-KM2A. The best fit out to ~60° is also shown.

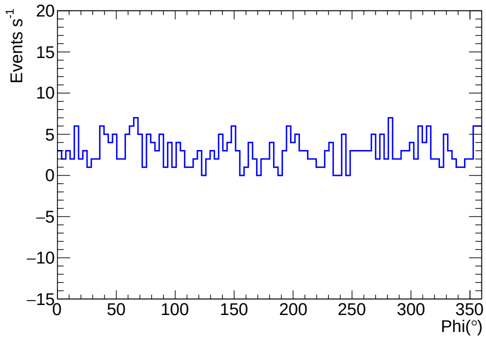


Figure 3: Azimuthal distribution of showers with a reconstructed zenith angle $\theta > 70°$.

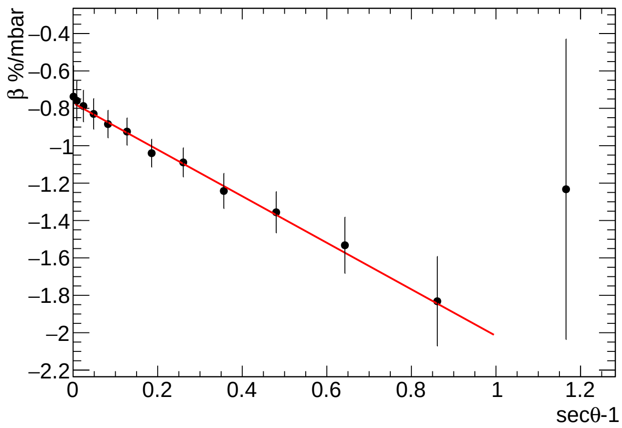


Figure 4: The barometric coefficient at different zenith angles measured by LHAASO-KM2A.

The MD is a pure water Cherenkov detector enclosed within a cylindrical concrete tank with an inner diameter of 6.8 m and a height of 1.2 m. An 8-inch PMT is installed at the center of the top of the tank to collect the Cherenkov light produced by high-energy particles as they pass through the water[5].

The whole detector is covered by a steel lid underneath soil. The thickness of the overburden soil is 2.5 m, which is used to absorb the secondary electrons/positrons. Thus the particles that can reach the water inside and produce Cherenkov signals are almost exclusively muons, except for those MDs located at the very central part of showers where some very high energy EM components may have a chance to punch through the screening soil layer.

For a typical MD, the detection efficiency to muons is >95%. The time resolution is about 10 ns. The charge resolution is <25% for a single muon. The dynamic range is from 1 to 10^4 particles. The average single rate is about 8 kHz with a threshold equivalent to 0.4 particles.

Nearly half of the KM2A array, including 2365 EDs and 578 MDs, covering an area of 432000 m^2 as shown in Fig.1, has been operating since 27 December 2019. The trigger logic of KM2A has been well tested[6]. For the first half-array, at least 20 EDs firing within a time window of 400

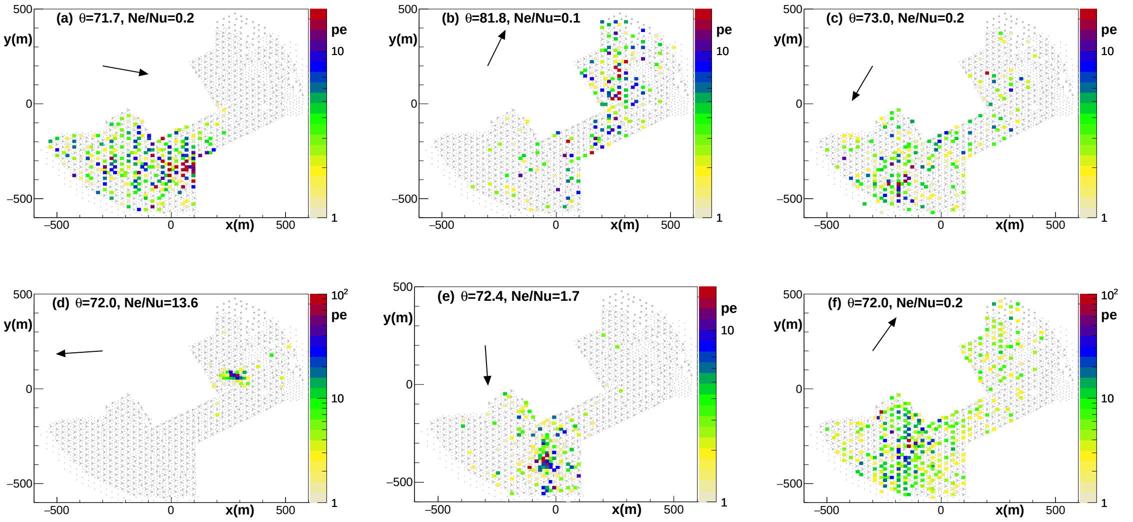


Figure 5: Display of events observed by LHAASO-KM2A with a reconstructed zenith angle $\theta > 70°$. The color scale shows the number of photo-electrons. The arrows show the reconstructed arrival directions.

ns is required for a shower trigger, thus yielding a negligible random noise trigger rate. The event trigger rate is about 1 kHz. For each event, the DAQ records 10 µs of data from all EDs and MDs that have signals over the thresholds[7, 8].

3. Results

At zenith angles $\theta > 60°$ an excess of events is observed above the rate of EAS as expected from the exponential absorption of the air shower electromagnetic component in the large atmospheric depth (see Fig.2).

In Fig.3 the shower rate as a function of the reconstructed azimuthal angle is shown. A flat distribution is observed according to the flat landscape around the LHAASO experiment. Moreover, the dependence of the barometric effect on the zenith angle, shown in Fig.4, clearly shows a deviation from the secθ behavior for sec$\theta > 2$. The barometric coefficient $\beta = \frac{1}{n}\frac{dn}{dx}$ (n = counting rate, x = atmospheric pressure) is related to zenith angle as $\beta(\theta) = \beta(0°)sec\theta$. This can be explained by the presence of a "non-attenuated" EAS component that dominates for angles larger than 60°.

In Fig. 5 some typical HAS events observed by LHAASO-KM2A are displayed. The ratio of N_e/N_μ in figure (a), (b), (c) and (f) is 0.2, 0.1, 0.2 and 0.2 respectively. These events show that the ratio of electromagnetic particles to muons is ≤ 1 as expected in HAS. The events shown in figures (d) and (e) with a ratio $N_e/N_\mu \geq 1$ probably due to shower fluctuations. We will deeply study the fluctuations associated to these interactions. Detailed MC simulations are under way to evaluate an optimum threshold value to optimize the HAS selection and to select possible neutrino-induced candidate events.

The arrival time of the shower is shown in Fig.6, which becomes clear after filtering out the noise hits via reconstruction. The color scale indicates the relative trigger time of the unit in ns.

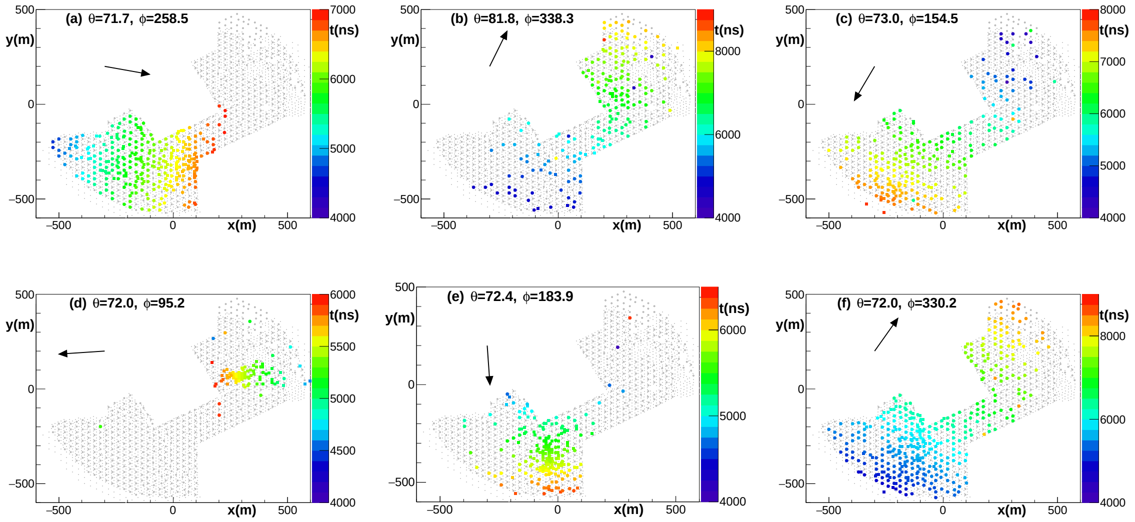


Figure 6: The arrival time of the shower observed by LHAASO-KM2A with a reconstructed zenith angle $\theta > 70°$. The color scale shows the relative trigger time of the detector in nanoseconds. The arrows show the reconstructed arrival directions. The reconstructed zenith and azimuth angles of different events are shown in the displays.

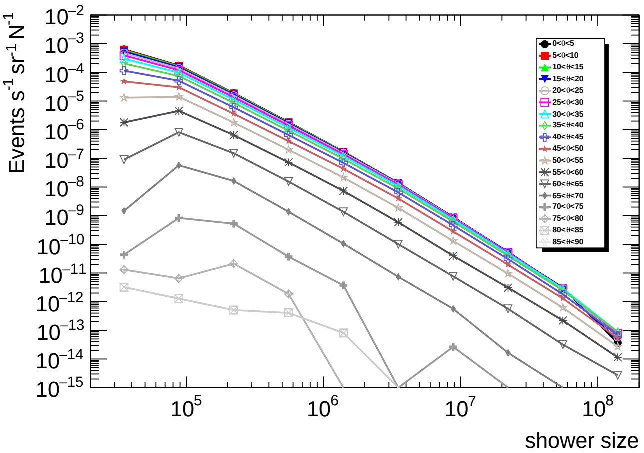


Figure 7: Differential size spectra measured by LHAASO-KM2A for different zenith angles.

θ and ϕ denote the zenith angle and azimuth angle of the event, respectively. The black arrows represent the incident direction of the event.

In Fig. 7 the shower rate measured by LHAASO-KM2A is shown, as a function of the size, for different primary zenith angles. The spectra soften with increasing angle up to about 70°, as can be appreciated in Fig. 8 where the best-fit spectral indices are plotted. In the zenith angle region 50° - 70° a quick transition to a value of about -3.6, characteristic of the EAS muon component, is observed.

In Fig. 9 (10) a preliminary comparison of reconstructed size (muon number) between data and MC simulations is shown. From simulations we can see that the energy range under investigations

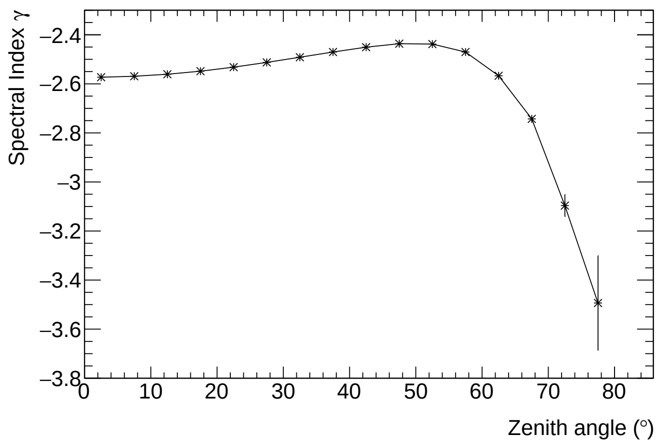
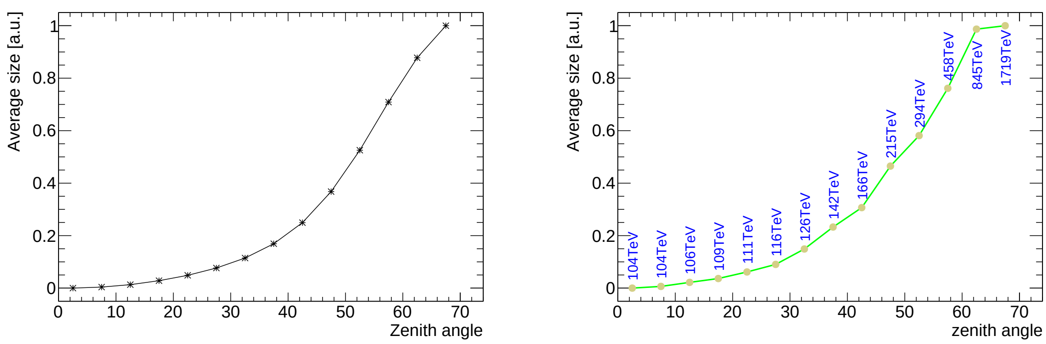
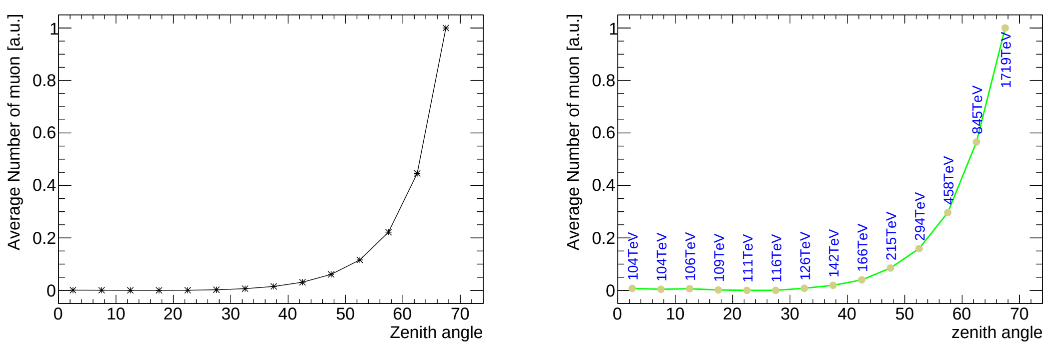


Figure 8: Best-fit spectral indices calculated for the spectra of Fig. 7.



(a) data (b) simulation

Figure 9: Comparison of average size between experimental data and simulation.



(a) data (b) simulation

Figure 10: Comparison of average muon number between experimental data and simulation.

with HAS is above 500 TeV. Detailed simulations of HAS are under-way.

4. Summary

In this work, the first observations of HAS with LHAASO-KM2A are presented. The zenith and azimuth angle distribution of EAS and the transition from electromagnetic-dominated showers to muon-dominated ones above a zenith angle of 60° are observed.

Our analysis, using half array data of LHAASO-KM2A, has shown that LHAASO can observe HAS and could be used to study muon content in EAS and search for neutrino-induced EAS from flaring phenomena like GRBs.

Acknowledgements: *This analysis is supported by PIFI program of the Chinese Academy of Sciences No.113111WGZJTPYJY20200004, the Natural Science Foundation of China No.U1931201.*

References

[1] Z. Cao et al. (LHAASO Collaboration), Nature, 594 (2021) 33–36.

[2] T. Matano et al., Phys. Rev. Lett., 15 (1965) 594-597.

[3] E. Bohm and M. Nagano, J. Phys., A6 (1973) 1262.

[4] G. Disciascio et al. POS (ICRC2013)1038

[5] H.H. He, Radiation Detection Technology and Methods 2, 7 (2018).

[6] S. Wu et al., Astroparticle Physics 103 (2018) 41-48.

[7] H. K. Lv et al., Astroparticle Physics 100 (2018) 22-28.

[8] F. Aharonian et al., Chinese Phys. C 45(2021)025002.