

# Evidence of cosmic-ray acceleration up to sub-PeV energies in the supernova remnant IC 443

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Supernova remnants (SNRs) have been considered as the primary contributors to cosmic rays (CRs) in our Galaxy. However, the maximum energy of particles that can be accelerated by shocks of SNRs is uncertain observationally and theoretically, and the role of contribution to CRs around PeV energies by SNRs is unclear. In this study, we present observations of high-energy  $\gamma$ -ray emission from the SNR IC 443 using the Large High Altitude Air Shower Observatory (LHAASO). The morphological analysis reveals a pointlike source whose location and spectrum are consistent with those of the Fermi-LAT-detected compact source with  $\pi^0$ -decay signature, and a more extended source which is consistent with a newly discovered source, previously unrecognized by Fermi-LAT. The spectrum of the point source can be described by a power-law function with an index of  $\sim 3.0$ , extending beyond  $\sim 30$  TeV without apparent cutoff. Assuming a hadronic origin of the  $\gamma$ -ray emission, the 95% lower limit of accelerated protons reaches about 300 TeV. The extended source might be coincident with IC 443, SNR G189.6+3.3 or the putative pulsar wind nebula CXOU J061705.3+222127, and can be explained by either a hadronic or leptonic model. The LHAASO results provide compelling evidence that CR protons up to sub-PeV energies can be accelerated by the SNR.

*Introduction.* — It is widely believed that Galactic sources have the capability to accelerate cosmic rays (CRs) up to energies in the knee region, which represents a distinct break in the CR spectrum around several PeV [1–4]. These sources, known as PeVatrons, remain elusive despite ongoing efforts to identify them. Supernova remnants (SNRs), which accelerate energetic particles via the diffusive shock acceleration mechanism, are considered to be promising candidates for PeVatrons [5]. With the nonlinear effect of the diffusive shock acceleration and the possible magnetic field amplification, SNRs are also expected to be able to accelerate CRs to PeV energies [5–7]. Observations of ultra-high-energy  $\gamma$ -ray emission from SNRs, particularly those interacting with dense molecular clouds (MC) [8], are expected to provide direct evidence of whether SNRs can serve as PeVatrons.

Usually three radiation mechanisms exist for understand-

ing  $\gamma$ -ray emission of SNRs, the hadronic process with  $\gamma$ -ray photons being produced via decay of neutral pions, the leptonic processes produced by accelerated electrons through the inverse Compton scattering off background photons and bremsstrahlung in the medium. In the ultra-high-energy regime, the  $\gamma$ -ray production from the inverse Compton scattering is limited by the Klein-Nishina suppression effect. Nonetheless, establishing a robust hadronic interpretation remains challenging due to the limited knowledge about SNRs themselves and their environment parameters. Gamma-ray observations in the sub-GeV band of several SNRs interacting with MCs found evidence of characteristic  $\pi^0$ -decay spectral bumps [9–11], making these objects ideal targets for probing hadronic CR acceleration.

IC 443 is a middle-aged SNR with an estimated age ranging from 3 to 30 thousand years [12–14], at a distance of approximately 1.5 kpc [15]. The interaction of IC 443 with surrounding MCs has been firmly established through the detection of OH maser emission [16–18] and various molecular lines [19–21]. The remnant exhibits a double-shell structure in both optical and radio wavelengths [22]. In the X-ray

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band, IC 443 is predominantly characterized by the thermal emission [23]. In terms of  $\gamma$ -ray emission, a relatively compact source with a Gaussian extension (39% containment) of about  $0.17^\circ$  and positionally coincides with shocked clouds was detected, and the  $\pi^0$ -decay bump in the sub-GeV spectrum was identified [9, 11], offering evidence of hadronic CR acceleration in the SNR shock. A possible bow-shock pulsar wind nebula (PWN), CXOU J061705.3+222127 was detected in radio and X-ray in the vicinity of the SNR, but its physical connection with IC 443 SNR has not been well established and the pulsation of the hypothetical pulsar is also not found yet [24, 25]. Recently, an extended source with bigger extension ( $R_{39} = 0.64^\circ$ ) overlapped with IC 443 has been reported [26], but no firm association has been identified. There exists a possible counterpart, SNR G189.6+3.3 with an extension of about  $0.75$  degrees, as detected by X-ray observations [27, 28]. The age of SNR G189.6+3.3 was estimated to be about  $10^5$  yr, and the distance is similar to that of IC 443 ( $\sim 1.5$  kpc) [27]. The centroids of the Fermi-LAT extended source and SNR G189.6+3.3 differ by about  $0.3^\circ$  which is within the source extensions. TeV emission from IC 443 was detected by MAGIC [29], VERITAS [30], and HAWC [31]. MAGIC identified a point-like source coincident with the densest part of the MCs and the position of the 1720 MHz OH maser, indicating a potential hadronic origin for the emission [29]. VERITAS observed an extended source, with the centroid and extension being consistent with the Fermi-LAT small source [30]. HAWC identified two sources in the IC 443 region, a point source positionally consistent with that detected by MAGIC and VERITAS, and the other extended one with the centroid near the pulsar B0611+22 and was postulated to be a pulsar halo [31]. HAWC did not find spectral cutoff of the point source component and inferred that protons up to 65 TeV can be accelerated by the SNR.

*LHAASO observation and data analysis.* — LHAASO is a ground-based extensive air shower experiment located at Haizi Mountain in China, with an average altitude of 4410 meters [32]. This hybrid array comprises the Kilometer Square Array (KM2A), the Water Cherenkov Detector Array (WCDA), and the Wide Field-of-view Cherenkov Telescope Array (WFCTA). The KM2A covers an area of  $1.3$  km<sup>2</sup>, and serves as the most sensitive  $\gamma$ -ray detector above 20 TeV. The WCDA covers a physical area of  $0.08$  km<sup>2</sup>, and can detect  $\gamma$  rays down to sub-TeV range. Both KM2A and WCDA arrays has a wide field-of-view of approximately 2 sr, making them well-suited for observing extended sources. The combination of these two arrays allow us to conduct detailed studies of  $\gamma$ -ray sources in a broad energy range.

This work uses the events collected by the WCDA, from March 5, 2021 to July 31, 2024, with a livetime of  $\sim 1136$  days, and the KM2A, from July 20, 2021, to December 31, 2024, with a livetime of  $\sim 1228$  days. We adopt the same selections as described in Ref. [33] to select candidate events. The events are binned with  $0.1^\circ \times 0.1^\circ$  grids to make the skymap. The “direct integration method” [34] is adopted to calculate the background.

IC 443 is about 6 degrees away from the Geminga pulsar and the large extended Geminga halo [35] may affect the anal-

ysis of IC 443. To properly account for this, the region of interest (ROI) is defined as a fan-shape region centered on Geminga pulsar, with a radius of 10 degrees and an opening angle of 90 degrees containing IC 443 in its center (see Fig. S1 in the Supplemental Material). Within the ROI, a diffusion template as  $f(\theta) \propto \frac{1}{\theta_d(\theta+0.113\theta_d)} e^{[-(\theta/\theta_d)^{1.52}]}$  (adapted from [36]) is adopted to describe Geminga halo emission, where  $\theta$  is the angular distance from Geminga pulsar and  $\theta_d$  is the characteristic diffusion width. Note that the Geminga halo exhibits an asymmetric morphology (to be published elsewhere), which has been taken into account in the current analysis. Nevertheless, within our chosen ROI, considering or neglecting this asymmetry leads to only minor differences in the results. The diffuse  $\gamma$ -ray emission [37, 38] is modelled using the gas template as traced by the PLANCK dust opacity [39] and a broken power-law spectrum. The gas template from gas surveys [40–42] is employed as a systematic uncertainty check.

The 3D-likelihood method is employed to simultaneously fit the morphology and spectrum of the relevant sources in the ROI, which include the target source IC 443, the Geminga halo, and the diffuse emission in our case. The test statistic (TS) is defined as  $TS = 2 \ln(\mathcal{L}/\mathcal{L}_0)$ , where  $\mathcal{L}_0$  is the maximum likelihood value for the null hypothesis and  $\mathcal{L}$  is the maximum likelihood for the source hypothesis.

*Results.* — The significance ( $\sqrt{\text{TS}}$ ) map of a  $3 \times 3$  deg<sup>2</sup> region centered at IC 443 for  $E > 0.5$  TeV derived with the LHAASO data, calculated for each  $0.1^\circ \times 0.1^\circ$  pixel assuming a point source in the pixel after subtracting the Geminga halo and the diffuse background, is shown in panel (a) of Fig. 1. Bright extended excess emission around IC 443 can be detected. Assuming a Gaussian morphology and an exponentially cutoff power-law (ECPL) spectrum,  $\phi(E) = \phi_0(E/3 \text{ TeV})^\alpha e^{-E/E_{\text{cut}}}$ , of the emission, it has been found that an extended source with a total significance (for  $E \geq 0.5$  TeV) of  $\sim 26\sigma$  is detected. The intrinsic extension (39% containment) of the source is found to be  $R_{39} = 0.38^\circ \pm 0.03^\circ$ , which is between the Fermi-LAT detected compact source and the more extended one.

We thus test whether the emission can be separated into two components. Via adding one more Gaussian template with a power-law (PL) spectrum,  $\phi = \phi_0(E/3 \text{ TeV})^{-\alpha}$ , we find that the overall TS value of the fitting increases by about 49 compared with the one-source hypothesis. Given 5 more free parameters, it means that the other source component is favored with a significance of  $6.0\sigma$ . The fitting results of different components are given in Table I. In the two-component hypothesis, the compact one (C0) is found to be a pointlike source with a significance of  $10.5\sigma$  and the 95% upper limit of the extension being  $0.27^\circ$ , and the extended one (C1) has a significance of  $13.1\sigma$  and an extension of  $R_{39} = 0.67^\circ \pm 0.07^\circ$ . The one-dimensional distribution of the integrated  $\gamma$ -ray fluxes from the rectangle box region labelled in panel (a), together with the profiles of C0 and C1 convolved with the point spread function (PSF), is given in panel (b). The zero point is chosen as the midpoint between C0 and C1. The dotted line shows the PSF profile centered at C0. This plot indicates that the total emission can indeed



Model	TS	Name	R.A. (°)	Dec. (°)	$R_{39}$ (°)	$\phi_0$ ( $10^{-14}$ TeV $^{-1}$ cm $^{-2}$ s $^{-1}$ )	$\alpha$	$E_{\text{cut}}$ (TeV)
Two	5630.5	C0	94.27±0.03	22.44±0.02	Point	3.51±0.43	2.95±0.07	-
Components		C1	94.45±0.07	22.61±0.06	0.67±0.07	17.20±2.74	2.53±0.14	19.65 ± 8.67
One Component	5581.5	...	94.33±0.03	22.52±0.02	0.38±0.03	15.13±1.56	2.68±0.08	34.22±14.62

TABLE I. Fitting results of centroids, extensions (39% containment), fluxes at 3 TeV, and spectral indices of different components for IC 443.

are different from the HAWC extended source. The LHAASO source C1 overlaps with SNR G189.6+3.3, with centroids differing by about  $0.47^\circ$ .

Green contours in panels (c) and (d) of Fig. 1 show the molecular gas distribution around IC 443 at similar distance ( $\sim 1.5$  kpc) as traced by the CO emission with velocities ranging from  $-10$  km/s to  $10$  km/s, observed by the Milky Way Imaging Scroll Painting (MWISP; [43]) project. There is strong evidence that interactions between the SNR shock and molecular clouds existing in the IC 443 region, such as the OH maser, line broadening and so on [18, 19]. Except the shocked clouds in the vicinity of the compact source C0 [19], there is extended molecular mass distribution in a wider region around source C1 (see panel (d) of Fig. 1). The results indicate that both sources may be produced by hadronic interactions between accelerated protons and the dense molecular gas.

A PL form is found to well describe the spectrum of C0. Fitting with an ECPL function results an increase of the TS value of 3.7, corresponding to a significance of  $1.9\sigma$ . For C1 component, the spectrum fitting favors an ECPL function, with a cutoff significance of  $\sim 5.1\sigma$ . The derived cutoff energy for C1 component is  $19.65 \pm 8.67$  TeV, which shows degeneracy with the spectral index. Fitting results of the spectral parameters are given in Table I. The spectral energy distributions (SED) of these two components are shown in Fig. 2. The SED data can be found in Table S2 in the Supplemental Material. Measurements of VHE emission by other experiments are also shown for comparison. The LHAASO SED of C0 is consistent with previous measurements, but extend to higher energies.

*Systematic uncertainties.* — The systematic uncertainty in the source location is primarily attributed to the pointing error, which is approximately  $0.04^\circ$  for WCDA and  $0.03^\circ$  for KM2A [33]. The systematic uncertainty on the source size is mainly due to the uncertainties of the PSF, and is estimated to be about  $0.05^\circ$  (for  $R_{39}$ ) for WCDA and  $0.08^\circ$  (for  $R_{39}$ ) for KM2A [33]. Regarding the flux measurements, the systematic uncertainties on the absolute flux are estimated to be about 9.6% for WCDA [44] and 7% for KM2A [45], due mainly to various kinds of model assumptions of the Monte Carlo simulation. The uncertainties of the diffuse  $\gamma$ -ray background and Geminga halo would affect the measurements of IC 443. Comparison of the results between the fittings assuming a fixed diffuse background [38] and a free diffuse background gives only slight impacts on the flux measurements of C1. Using the gas map from gas surveys as diffuse template results in very minor changes of the results of both C0 and C1. While the detailed analysis of the Geminga halo will be published elsewhere, we study the impact on IC 443 due to the un-

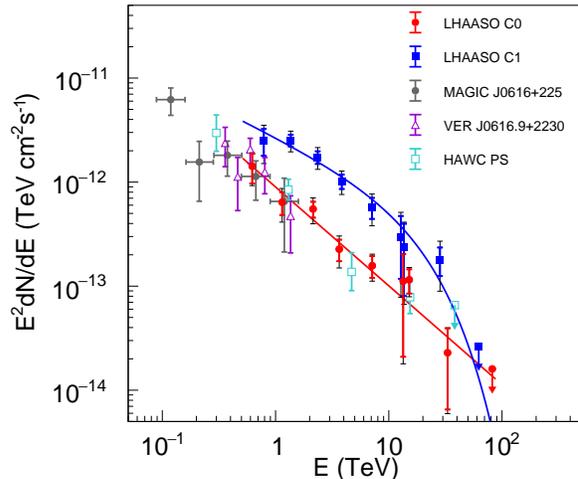


FIG. 2. The SEDs of the two sources C0 and C1, with statistical errors (red) and total errors including statistical and systematic ones (black). Arrows show the 95% confidence level upper limits, and solid lines show the best-fitting spectra of the two sources. Results measured by MAGIC [29], VERITAS [30], and HAWC [31] are also shown.

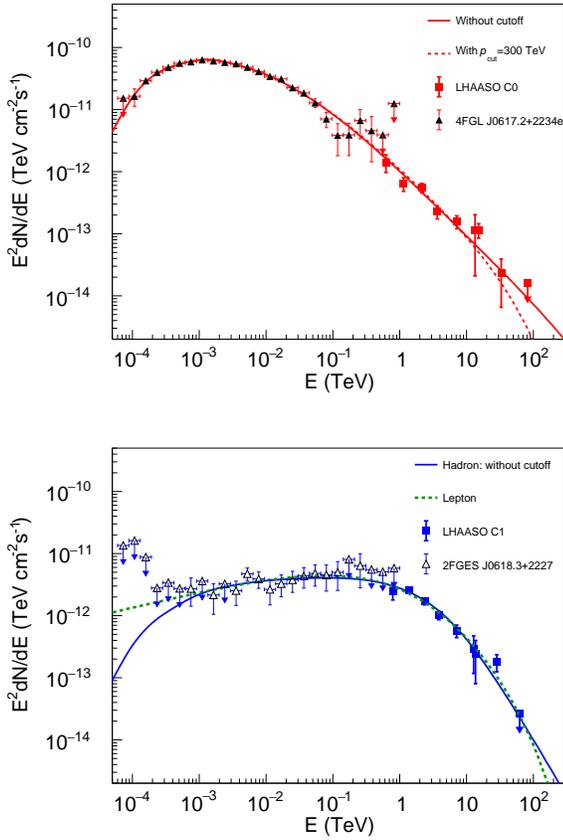
certainty of the morphology assumption of the Geminga halo, and find again the main impacts are on fluxes of source C1 for  $E > 20$  TeV. See Sec. II and Fig. S2 in the Supplemental Material for more details. The total systematic uncertainties on the SEDs are added in quadrature to the statistical ones and are shown by black errorbars in Fig. 2.

*Discussion.* — The LHAASO source C0 is morphologically consistent with the Fermi-LAT compact source with  $\pi^0$ -decay signature. The spectrum also nicely connect with that of Fermi-LAT (see Sec. IV and Table S3 in the Supplemental Material which includes Refs. [46–48] for the re-analysis of Fermi-LAT data), suggesting that it is very likely to be the high energy counterpart of the Fermi-LAT source. The wide-band  $\gamma$ -ray emission can be modelled with a hadronic model. The proton spectrum around the SNR is parameterized as a broken power-law distribution with an exponential cutoff

$$Q(p) = Q_0 p^{-s_1} [1 + (p/p_{\text{br}})^{s_2-s_1}]^{-1} e^{-p/p_{\text{cut}}}, \quad (1)$$

where  $p$ ,  $p_{\text{br}}$ , and  $p_{\text{cut}}$  are the momentum, break momentum, and cutoff momentum of protons,  $s_1$  and  $s_2$  are spectral indices below and after  $p_{\text{br}}$ . The spectral break is required to fit the Fermi-LAT data [11]. Note that the parameter  $p_{\text{cut}}$  is a characteristic number to describe the spectral behavior of

329 protons at the highest end, and may not directly correspond<sup>347</sup>  
 330 to the cutoff energy of  $\gamma$ -ray photons. Using the  $\gamma$ -ray yield<sup>348</sup>  
 331 parameterization of Ref. [49], we obtain the expected  $\gamma$ -ray<sup>349</sup>  
 332 spectra as shown in the top panel of Fig. 3. Here we assume<sup>350</sup>  
 333 an average gas density of  $20 \text{ cm}^{-3}$  [11]. Since no significant  
 334 spectral cutoff of the LHAASO spectrum of C0 is found, we  
 335 assume  $p_{\text{cut}} = \infty$ , and **get the proton spectrum parameters**  
 336 **as:**  $s_1 = 2.28^{+0.03}_{-0.02}$ ,  $s_2 = 3.13^{+0.05}_{-0.06}$ ,  $p_{\text{br}} = 0.38^{+0.16}_{-0.13} \text{ TeV}$ , and  
 337  $W_p = 5.67^{+0.57}_{-0.57} \times 10^{49} (n/20 \text{ cm}^{-3})^{-1} \text{ erg}$  **which is the total en-**  
 338 **ergy of protons with kinetic energy above 1 GeV.** Compar-  
 339 ison of the model fitting spectrum with the measurements by  
 340 Fermi-LAT and LHAASO is shown in the top panel of Fig. 3.



370 FIG. 3. Gamma-ray spectra of C0 (top panel) and C1 (bottom panel)<sup>370</sup>  
 371 as measured by Fermi-LAT and LHAASO. Solid lines in the plots<sup>371</sup>  
 372 show the hadronic model predictions of the spectra, assuming no<sup>372</sup>  
 373 spectral cutoff of protons ( $p_{\text{cut}} = \infty$ ). In the top panel, the dashed<sup>373</sup>  
 374 line shows the hadronic model flux for  $p_{\text{cut}} = 300 \text{ TeV}$  (for C0), and<sup>374</sup>  
 375 in the bottom panel, the dashed line shows the prediction of a lep-<sup>375</sup>  
 376 tonic model (for C1).<sup>376</sup>

341 We can derive a constraint on the cutoff energy of accel-  
 342 erated protons for source C0. Fig. 4 shows the probability  
 343 distribution of the inverse of cutoff parameter,  $1/p_{\text{cut}}$ . Both  
 344 the Fermi-LAT data and the LHAASO data are included in  
 345 the likelihood computation, and the other spectral parameters  
 346 are left free to be optimized in the calculation. The 95% up-

per limit<sup>1</sup> of  $1/p_{\text{cut}}$  is found to be about  $0.0034 \text{ TeV}^{-1}$ , as la-  
 belled by the vertical line. This corresponds to a lower limit  
 of  $p_{\text{cut}} \approx 300 \text{ TeV}$ . As a comparison, we also show the model  
 curve with  $p_{\text{cut}} = 300 \text{ TeV}$  by the dashed line in Fig. 3.

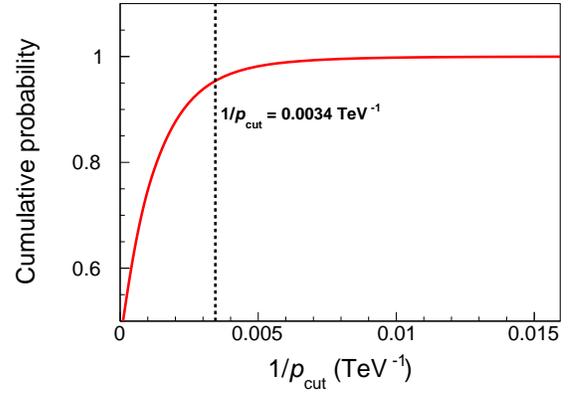


FIG. 4. Cumulative probability distribution of parameter  $1/p_{\text{cut}}$  for  
 source C0. The 95% lower limit on  $1/p_{\text{cut}}$  is  $0.0034 \text{ TeV}^{-1}$ , as indicated  
 by the vertical dashed line, corresponding to  $p_{\text{cut}} \approx 300 \text{ TeV}$ .

351 The LHAASO source C1 could be the counterpart of Fermi-  
 352 LAT extended source, and may be related with IC 443, SNR  
 353 G189.6+3.3, or CXOU J061705.3+222127. The broadband  
 354 SED from GeV to 100 TeV for source C1 is distinct from that  
 355 of C0. Assuming also a hadronic emission mechanism, **we**  
 356 **obtain the proton spectrum parameters as:**  $s_1 = 1.94^{+0.06}_{-0.10}$ ,  
 357  $s_2 = 3.78^{+0.46}_{-0.28}$ ,  $p_{\text{br}} = 22.6^{+13.62}_{-8.30} \text{ TeV}$ , and  $W_p = 8.18^{+0.85}_{-0.83} \times$   
 358  $10^{49} (n/1 \text{ cm}^{-3})^{-1} \text{ erg}$ . Note that, although using the ECPL  
 359 model to fit the LHAASO data favors a spectral cutoff of C1,  
 360 its wide-band spectral behavior affects the fitting result. When  
 361 using Eq. (1) to describe the proton spectrum, we find that  
 362 the spectral cutoff of C1 is also insignificant (the TS value  
 363 increases by about 1.24 compared with infinite cutoff). The  
 364 solid line in the bottom panel of Fig. 3 shows the hadronic  
 365 model fitting result for  $p_{\text{cut}} = \infty$ . The apparent proton spec-  
 366 trum for C1 is different from that of C0. If these two sources  
 367 have the same origin from IC 443, the spectral difference may  
 368 be explained as a propagation effect of particles, which re-  
 369 sults in a suppression of low-energy particles due to inefficient  
 370 propagation [51]. Note, however, although there is molecu-  
 371 lar gas distribution in the extension region of source C1, the  
 372 morphology of C1 does not show clear correlation with the  
 373 gas distribution. Alternatively, a leptonic scenario with the  
 374 inverse Compton scattering emission of accelerated electrons  
 375 may also explain the measurements, as shown by the dashed  
 376 line in the bottom panel of Fig. 3. Here the background radia-  
 377 tion fields are approximated with two gray body components

<sup>1</sup> Note that, the probability distribution of  $1/p_{\text{cut}}$  is single-sided since we restrict  $1/p_{\text{cut}}$  to be positive. There is one half probability that the statistical fluctuation gives negative result of  $1/p_{\text{cut}}$  is eliminated [50]. We thus add this probability to  $1/p_{\text{cut}} = 0$  and integrate to a cumulative probability of 0.95.

including the cosmic microwave background with a temperature of 2.725 K and an energy density of  $0.26 \text{ eV cm}^{-3}$ , an infrared background with a temperature of 30 K and an energy density of  $1.0 \text{ eV cm}^{-3}$  [11]. Parameters for electrons are:  $s_1 = 2.49^{+0.40}_{-1.12}$ ,  $s_2 = 3.84^{+1.12}_{-0.47}$ ,  $p_{\text{br}} = 3.66^{+16.08}_{-3.00} \text{ TeV}$ ,  $W_e = 2.12^{+12.04}_{-1.96} \times 10^{48} \text{ erg}$  and a fixed cutoff energy  $p_{\text{cut}} = 125 \text{ TeV}$ , which corresponding to the cooling energy of electrons in the above background photon fields and a  $3 \mu\text{G}$  magnetic field for an age of  $\sim 10 \text{ kyr}$  (IC 443). The effective propagation distance [52] is about  $\sqrt{2Dt} \approx 17 \text{ pc}$  for a slow diffusion coefficient [35], which is also consistent with the extension of C1 (the 39% containment radius of  $\sim 17.5 \text{ pc}$ ). However, if source C1 is associated with SNR G189.6+3.3, the parameters will be different from the above estimate. Another possibility of C1 is the halo emission associated with the PWN CXOU J061705.3+222127, although the position of the PWN deviates from the centroid of C1 by about 0.3 degrees and the age of the PWN seems to be somehow young. At present it is difficult to judge which one explains the data better than the other, and we need additional multi-wavelength measurements to further test the nature of source C1.

*Conclusion.* — The SNR-MC interacting systems are believed to be ideal targets to probe acceleration of hadronic CRs by SNR shocks. Some of these systems exhibit characteristic  $\pi^0$ -decay bumps in their  $\gamma$ -ray spectra, strengthening the evidence that SNRs are one class of sources of Galactic CRs. In this work, we carry out detailed study of the morphology and spectrum of very high energy  $\gamma$ -ray emission from such an example, the region of SNR IC 443, with the LHAASO data. Two sources have been resolved in the data, one is a point source (C0) coincides with the compact source detected by Fermi-LAT, MAGIC, VERITAS, and HAWC which has both the interaction with MCs and the  $\pi^0$ -decay bump, and the other is an extended source (C1) coincides with the newly reported Fermi-LAT source 2FGES J0618.3+2227. The spectrum of C0 is well described by a PL shape without significant cutoff, and the spectrum of C1 can be described by an ECPL shape. The LHAASO SED of source C0 connects smoothly with the Fermi-LAT compact source, and the wide-band  $\gamma$ -ray SED can be well modelled with a hadronic scenario. We derive the 95% lower limit of the cutoff momentum of protons for source C0 to be  $\sim 300 \text{ TeV}$ , providing compelling evidence

that the SNR shock can accelerate protons to sub-PeV energies. The location and extension of source C1 are consistent with the Fermi-LAT extended one, and the SEDs are also consistent with each other at overlapping energies. Distributed molecular gas exist in the sky region of the source, indicating that the  $\gamma$ -ray emission may have a hadronic origin. The proton spectrum to account for the wide-band SED of C1 is different from that of C0, which may be interpreted as a propagation effect of escaping protons. Alternatively, a leptonic scenario can also explain the  $\gamma$ -ray emission of C1.

## ACKNOWLEDGMENTS

We would like to thank all staff members who work at the LHAASO site 4400 m above the sea level year-round to maintain the detector and keep the water recycling system, electricity power supply, and other components of the experiment operating smoothly. We are grateful to Chengdu Management Committee of Tianfu New Area for the constant financial support for research with LHAASO data. We appreciate the computing and data service support provided by the National High Energy Physics Data Center. This work is supported by the following grants: the National Natural Science Foundation of China (Nos. 12220101003, 12322302, 12573053), the CAS Project for Young Scientists in Basic Research (No. YSBR-061), the Natural Science Foundation for General Program of Jiangsu Province of China (No. BK20242114), and the Jiangsu Provincial Excellent Postdoctoral Program (No. 2022ZB472), the National Science and Technology Development Agency (NSTDA) of Thailand, and the National Research Council of Thailand (NRCT) under the High-Potential Research Team Grant Program (N42A650868). This study made use of the data from the Milky Way Imaging Scroll Painting (MWISP) project, which is a multi-line survey in 12CO/13CO/C18O along the northern galactic plane with the PMO-13.7m telescope. We are grateful to all the members of the MWISP working group, particularly the staff members at the PMO-13.7m telescope, for their long-term support. MWISP was sponsored by National Key Research and Development Program of China with grants 2023YFA1608000, 2017YFA0402701, and by CAS Key Research Program of Frontier Sciences with grant QYZDJ-SSW-SLH047.

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Supplemental Material of “Evidence of cosmic-ray acceleration up to sub-PeV energies  
in the supernova remnant IC 443”  
(The LHAASO collaboration)

## I. ROI OF THE ANALYSIS

The ROI of the analysis is a fan-shaped region centered at Geminga pulsar with an opening angle of  $90^\circ$ , as shown in the left panel of Fig. S1. The radial distributions of C0 and C1 differ significantly from those of the diffuse emission and the Geminga halo, as illustrated in the right panel of Fig. S1. Since C0 and C1 are about 6 degrees away from Geminga, the radial profile of Geminga around C0 and C1 is relatively flat. Besides, enlarging or reducing the opening angle of fan-shaped region by  $20^\circ$  have been tested, and the results are almost unchanged.

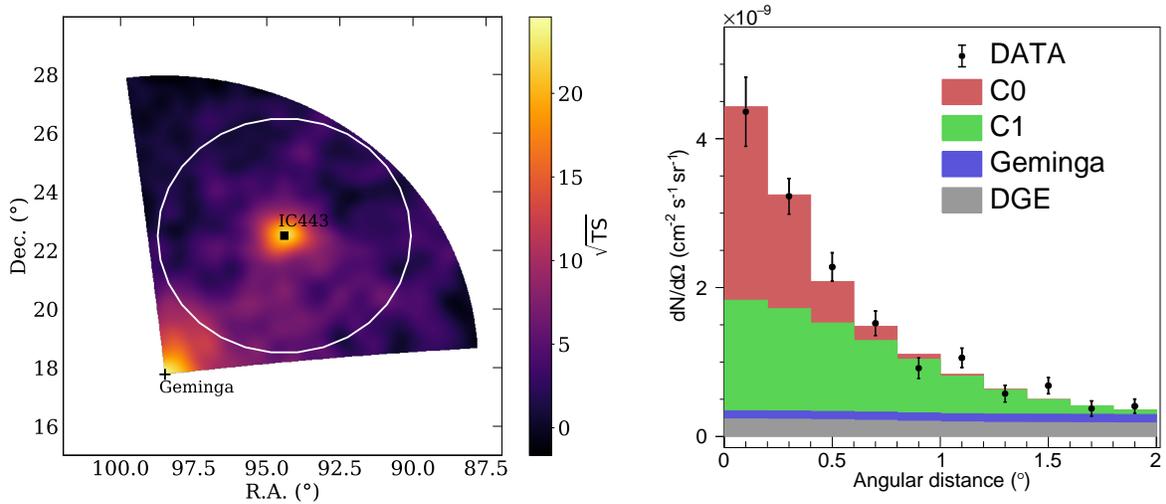


FIG. S1. Left: the fan-shaped region of interest (ROI) of this analysis, with the white circle denoting a  $4^\circ$  radius centered on IC 443. Right: the one-dimensional radial distribution of the integrated  $\gamma$ -ray fluxes above 1 TeV for different components, centered at the midpoint between C0 and C1.

## II. SYSTEMATIC UNCERTAINTIES

The diffuse emission may have some impacts on the measurements of IC 443. We compare the results for two assumptions of the diffuse emission, with fixed flux from the outer Galactic plane [38] and a free flux normalization. The results are shown in the left panel of Fig. S2. The TS value decreases by about 15 when we fix the diffuse flux normalization, and the flux from the diffuse component is higher than the average flux from the outer Galactic plane [38]. However, the results of IC 443 are affected very slightly by different diffuse emission assumptions. Results of all parameters of sources C0 and C1 are consistent within statistical errors. A different diffuse emission template from the gas surveys (HI, H<sub>2</sub>, and HII) has been tested, and very minor differences on the results of C0 and C1 have been found (see Table S1).

The Geminga halo extends to the region of IC 443 and may affect the analysis of IC 443. The Geminga halo shows asymmetric morphology which has been used as the benchmark of this analysis. As a test, using the symmetric morphology for Geminga in this analysis decreases the total TS value of the two sources C0 and C1 by only 1.2, suggesting that no strong asymmetry exists in the ROI. The fitting results of C0 and C1 are consistent with the benchmark setting (Table S1). In addition, for the benchmark setting of this work, we assume that the energy-dependence of the extensions of Geminga halo follows a power-law form. To address this impact, we leave the extension parameter ( $\theta_d$ ) of Geminga free in each energy bin, and re-derive the fluxes of IC 443. The differences in the resulting SEDs are shown in the right panel of Fig. S2. It is shown that for  $E < 20$  TeV the results are in good agreement with each other, and slight differences exist for higher energies.

Other systematic uncertainties on the absolute flux measurements are estimated to be about 9.6% for WCDA [44] and 7% for KM2A [45], due mainly to various kinds of model assumptions of the Monte Carlo simulation. All the systematic uncertainties are added in quadrature to get the total systematic uncertainties of the flux measurements.

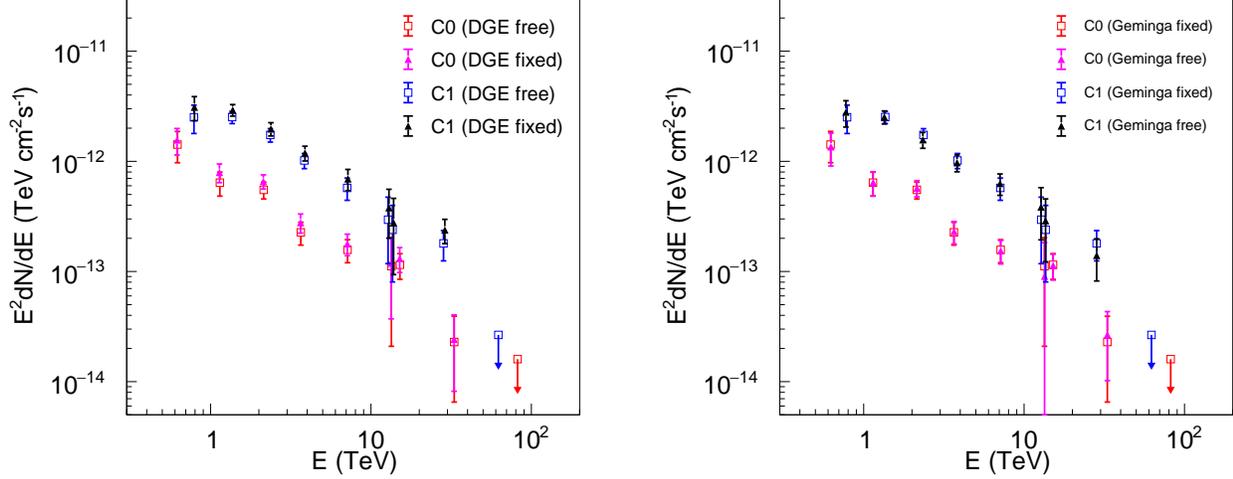


FIG. S2. Impact of the diffuse emission (left panel) and Geminga halo (right panel) on the SEDs of sources C0 and C1.

Model	$\Delta TS$	R.A. ( $^{\circ}$ )	Dec. ( $^{\circ}$ )	$R_{39}$ ( $^{\circ}$ )	Flux @ 3 TeV ( $10^{-14} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ )	$\alpha$	$E_{\text{cut}}$ (TeV)	$\Phi_0$ (DGE) ( $\text{TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ )	Comment
C0		$94.27 \pm 0.03$	$22.44 \pm 0.02$	$0.01 \pm 0.20$	$3.51 \pm 0.43$	$2.95 \pm 0.07$	–	$5.35 \pm 0.37$	Benchmark
C1		$94.45 \pm 0.07$	$22.61 \pm 0.06$	$0.67 \pm 0.07$	$17.20 \pm 2.74$	$2.53 \pm 0.14$	$19.65 \pm 8.67$	(Planck)	
C0	-15.3	$94.28 \pm 0.03$	$22.45 \pm 0.02$	$0.07 \pm 0.21$	$4.09 \pm 0.39$	$2.97 \pm 0.06$	–	3.84	DGE fixed
C1		$94.43 \pm 0.06$	$22.59 \pm 0.07$	$0.82 \pm 0.08$	$19.98 \pm 2.15$	$2.53 \pm 0.10$	$22.01 \pm 8.11$	(Planck)	
C0	+0.6	$94.27 \pm 0.03$	$22.44 \pm 0.02$	$0.01 \pm 0.20$	$3.45 \pm 0.40$	$2.95 \pm 0.07$	–	$6.32 \pm 0.44$	DGE template from gas survey
C1		$94.42 \pm 0.06$	$22.60 \pm 0.06$	$0.66 \pm 0.06$	$16.98 \pm 2.18$	$2.52 \pm 0.12$	$22.01 \pm 6.86$	(gas survey)	
C0	-1.2	$94.27 \pm 0.03$	$22.44 \pm 0.02$	$0.01 \pm 0.20$	$3.48 \pm 0.34$	$2.96 \pm 0.07$	–	$6.50 \pm 0.45$	Symmetric Geminga in the ROI
C1		$94.42 \pm 0.07$	$22.59 \pm 0.06$	$0.67 \pm 0.05$	$16.61 \pm 2.11$	$2.49 \pm 0.12$	$21.07 \pm 6.80$	(Planck)	

\* DGE spectrum:  $\Phi = \Phi_0 \cdot 10^{-14} (E/10 \text{ TeV})^{-2.72} [1 + (E/27.86 \text{ TeV})^5]^{(2.72-2.92)/5}$  [38].

TABLE S1. Impacts on the results of IC 443 for different settings.

### III. LHAASO FLUXES OF SOURCES C0 AND C1

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Table S2 give the measured fluxes of source C0 and C1 by LHAASO, with statistical and systematic uncertainties.

C0		C1	
$E$ (TeV)	$E^2 dN/dE \pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$ ( $\text{TeV cm}^{-2} \text{ s}^{-1}$ )	$E$ (TeV)	$E^2 dN/dE \pm \sigma_{\text{stat}} \pm \sigma_{\text{sys}}$ ( $\text{TeV cm}^{-2} \text{ s}^{-1}$ )
0.62	$(1.42 \pm 0.45 \pm 0.21) \times 10^{-12}$	0.79	$(2.51 \pm 0.72 \pm 0.70) \times 10^{-12}$
1.14	$(6.40 \pm 1.57 \pm 1.65) \times 10^{-13}$	1.36	$(2.52 \pm 0.32 \pm 0.47) \times 10^{-12}$
2.14	$(5.51 \pm 0.96 \pm 1.20) \times 10^{-13}$	2.36	$(1.74 \pm 0.24 \pm 0.32) \times 10^{-12}$
3.65	$(2.26 \pm 0.53 \pm 0.56) \times 10^{-13}$	3.84	$(1.02 \pm 0.16 \pm 0.20) \times 10^{-12}$
7.14	$(1.57 \pm 0.37 \pm 0.26) \times 10^{-13}$	7.11	$(5.74 \pm 1.31 \pm 1.43) \times 10^{-13}$
15.15	$(1.15 \pm 0.30 \pm 0.20) \times 10^{-13}$	13.63	$(2.39 \pm 1.59 \pm 0.67) \times 10^{-13}$
13.40	$(1.12 \pm 0.91 \pm 0.24) \times 10^{-13}$	12.78	$(2.95 \pm 1.77 \pm 1.25) \times 10^{-13}$
33.04	$(2.29 \pm 1.64 \pm 0.43) \times 10^{-14}$	28.33	$(1.80 \pm 0.55 \pm 0.72) \times 10^{-13}$
82.20	$< 1.60 \times 10^{-14}$	62.25	$< 2.66 \times 10^{-14}$

TABLE S2. Fluxes of LHAASO sources C0 and C1, with  $1\sigma$  statistical and systematic uncertainties.

## IV. FERMI-LAT ANALYSIS

$\log(E/\text{MeV})$	$\phi_{4\text{FGL}} (\text{MeV}^{-1}\text{cm}^{-2}\text{s}^{-1})$	$\phi_{2\text{FGES}} (\text{MeV}^{-1}\text{cm}^{-2}\text{s}^{-1})$
1.78–1.95	$< 2.88 \times 10^{-9}$	$< 2.55 \times 10^{-9}$
1.95–2.12	$(1.42 \pm 0.44) \times 10^{-9}$	$< 1.40 \times 10^{-9}$
2.12–2.28	$(1.16 \pm 0.14) \times 10^{-9}$	$< 3.49 \times 10^{-10}$
2.28–2.45	$(7.28 \pm 0.30) \times 10^{-10}$	$< 5.10 \times 10^{-11}$
2.45–2.62	$(4.03 \pm 0.15) \times 10^{-10}$	$< 2.86 \times 10^{-11}$
2.62–2.79	$(2.15 \pm 0.05) \times 10^{-10}$	$< 1.06 \times 10^{-11}$
2.79–2.96	$(1.04 \pm 0.02) \times 10^{-10}$	$(4.83 \pm 2.32) \times 10^{-12}$
2.96–3.13	$(5.17 \pm 0.09) \times 10^{-11}$	$< 2.94 \times 10^{-12}$
3.13–3.29	$(2.28 \pm 0.04) \times 10^{-11}$	$(8.06 \pm 4.13) \times 10^{-13}$
3.29–3.47	$(9.92 \pm 0.19) \times 10^{-12}$	$< 5.60 \times 10^{-13}$
3.47–3.64	$(4.33 \pm 0.10) \times 10^{-12}$	$(2.00 \pm 0.84) \times 10^{-13}$
3.64–3.80	$(1.75 \pm 0.05) \times 10^{-12}$	$(1.72 \pm 0.41) \times 10^{-13}$
3.80–3.97	$(6.84 \pm 0.24) \times 10^{-13}$	$(6.51 \pm 1.91) \times 10^{-14}$
3.97–4.14	$(2.63 \pm 0.12) \times 10^{-13}$	$(2.03 \pm 0.89) \times 10^{-14}$
4.14–4.31	$(1.10 \pm 0.06) \times 10^{-13}$	$(1.15 \pm 0.44) \times 10^{-14}$
4.31–4.48	$(3.65 \pm 0.29) \times 10^{-14}$	$(6.11 \pm 2.27) \times 10^{-15}$
4.48–4.65	$(1.38 \pm 0.15) \times 10^{-14}$	$(3.24 \pm 1.17) \times 10^{-15}$
4.65–4.82	$(4.38 \pm 0.71) \times 10^{-15}$	$(1.63 \pm 0.61) \times 10^{-15}$
4.82–4.99	$(1.11 \pm 0.31) \times 10^{-15}$	$(7.08 \pm 3.17) \times 10^{-16}$
4.99–5.16	$(2.78 \pm 1.48) \times 10^{-16}$	$(3.59 \pm 1.76) \times 10^{-16}$
5.16–5.32	$(1.29 \pm 0.69) \times 10^{-16}$	$< 2.68 \times 10^{-16}$
5.32–5.49	$(1.02 \pm 0.50) \times 10^{-16}$	$(9.70 \pm 5.44) \times 10^{-17}$
5.49–5.66	$(3.20 \pm 2.19) \times 10^{-17}$	$< 3.86 \times 10^{-17}$
5.66–5.83	$< 1.26 \times 10^{-17}$	$< 1.64 \times 10^{-17}$
5.83–6.00	$< 1.85 \times 10^{-17}$	$< 8.59 \times 10^{-18}$

TABLE S3. Fluxes with  $1\sigma$  uncertainties for sources 4FGL J0617.2+2234e and 2FGES J0618.3+2227 measured by Fermi-LAT.

In this work, we re-analyze the Fermi-LAT data of the IC 433 region with larger data set. The newest reconstructed P8R3 SOURCE Fermi-LAT data<sup>2</sup> are used in this analysis [46]. We select the data recorded from August 4, 2008 to February 5, 2025, 870 weeks in total. To verify the  $\pi^0$ -decay bump observed from IC 443, photons with energies down to 60 MeV are selected. To suppress the contamination from  $\gamma$ -rays generated by cosmic ray interactions in the upper layers of the atmosphere, photons collected at zenith angles larger than  $90^\circ$  are removed. Moreover, we filter the data using the specification (DATA\_QUAL>0) && (LAT\_CONFIG==1) to select good time intervals in which the satellite was working in the standard data taking mode and the data quality is good. We bin the data, from 60 MeV to 1 TeV, into 50 logarithmically distributed energy bins and  $200 \times 200$  spatial bins with size  $0.1^\circ$  centered at IC 443. We employ the binned likelihood analysis method to analyze the data with Fermitools version 2.2.0<sup>3</sup>. The instrument response function (IRF) adopted is P8R3\_SOURCE\_V3. The energy dispersion may be important for the analysis with low energy data, and is taken into account in the likelihood fitting. For the diffuse background emissions, we take the Galactic diffuse model gll\_iem\_v07.fits and the isotropic background spectrum iso\_P8R3\_SOURCE\_V3.v1.txt as recommended by the Fermi-LAT collaboration<sup>4</sup>. The source model XML file is generated using the user contributed tool make4FGLxml.py<sup>5</sup> based on the 4FGL source catalog [47,48], including the new extended source with the same coordinate and extension as reported in Ref. [26] and a power-law spectrum. We first make a broadband fitting to get the best fitted parameters for sources in the region of interest. Due to the large PSF of Fermi-LAT at low energies, we re-select data from 60 MeV to about 200 MeV with an extra cut of PSF3 to reduce the degeneracy between IC 443 and the new extended source. Further, for this data set, IRF P8R3\_SOURCE\_V3::PSF3 is adopted and the isotropic background spectrum iso\_P8R3\_SOURCE\_PSF3\_V3.v1.txt is used to match the data cut. Then we extract the SEDs, 60 MeV to about 200 MeV from the PSF3 data set and above about 200 MeV from the original data set, for IC 443 and the new extended source with other point

<sup>2</sup> <https://fermi.gsfc.nasa.gov/ssc/data/access/><sup>3</sup> <https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/><sup>4</sup> <http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html><sup>5</sup> <http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/>

645 sources parameters fixed to the best-fitting values obtained above. The obtained fluxes are reported in Table S3. Compared with  
646 previous Fermi-LAT analyses, our results for the large extended source are well consistent with those given in Ref. [26]. For  
647 the compact source, our derived fluxes agree well with the spectrum in the 4FGL catalog [47], but are slightly lower than those  
648 reported in Ref. [11]. Such differences might be attributed to the data processed with state-of-the-art event reconstruction in this  
649 work.