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Highlights from the Tibet ASγ experiment

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The Tibet ASγ experiment, observing cosmic rays/gamma rays above a few TeV, is located at 4,300m above sea level, in Tibet, China. The experiment is composed of a 65,700 m^2 surface air shower array and 3,400 m^2 underground water Cherenkov muon detectors. The surface air shower array is used for reconstructing the primary particle energy and direction, while the underground muon detectors are used for discriminating gamma-ray induced muon-poor air showers from cosmic-ray (proton, helium,...) induced muon-rich air showers. Furthermore, the underground muon detectors turn out to be effective to select the proton component in cosmic rays. We present the recent progress on analysis method for the proton energy spectrum in the hundred TeV region by means of proton selection by the underground muon detector information, and on the recent 100 TeV gamma-ray observation. In addition, we discuss the modelling of the cosmic-ray anisotropy observed in the TeV region.

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In this proceeding paper, highlights from the Tibet ASγ experiment, mostly the progress made by the Tibet ASγ experiment after ICRC2021 will be presented.

1. Gamma-ray observation

Cosmic rays are supposed to be accelerated up to the Knee energy (PeV) region a t cosmic-ray acceleration sites (for example, supernova remnants (SNRs), star-f ormation regions, the galactic center in our galaxy). Therefore, we naturally e xpect gamma rays above 100 TeV which originate in π^0 decays produced by the accelerated cosmic rays interacting with interstellar matter surrounding t he acceleration sites. The gamma-ray emission of electron origin may be highly suppressed above 10 TeV due to rapid decrease of inverse-Compton cross section by the Klein-Nishina effect as well as synchrotron radiation energy loss in the strong magnetic field around the acceleration sites. The detection and spectra l measurement of gamma rays in the sub-PeV/PeV region from their celestial sour ces, together with multi-wavelength (radio, X-ray, gamma-ray, and neutrino) obs ervations, will be a key experiment enabling us to discriminate between the two processes (cosmic-ray/electron origins), to locate and unravel the acceleratio n sites in our galaxy.

In the meanwhile, gamma rays above 100 TeV which is called Ultra-High-Energy (UHE) had not been detected until the Tibet ASγ experiment succeeded in the first detection of gamma rays beyond 100 TeV from the Crab[1] at 5.6 σ. Thus, the UHE gamma-ray astronomy was initiated by the Tibet ASγ experiment in 2019. The Crab UHE gamma-ray energy spectrum measured by the Tibet ASγ experiment was confirmed by the HAWC[2], MAGIC[3], LHAASO[4] experiments later. Subsequently, a dozen of UHE gamma ray sources have been detected by the Tibet ASγ, HAWC[5], LHAASO[6] experiments, as of 2021.

Sub-PeV galactic diffuse gamma rays were discovered by the Tibet ASγ experiment[9]. 38 gamma-ray-like events survive after the cut above 398 TeV, and 23 gamma-ray-like events are observed along the galactic disk within $|b| < 10°$ against low (2.73) cosmic-ray background events [9] estimated by real cosmic-ray data. The high galactic-latitude events ($|b| > 20°$) are assumed to be the cosmic-ray background events in this analysis. The highest-energy event among the 23 events along the galactic plane has unprecedentedly as high as 957 TeV, nearly 1 PeV. Surprisingly, the observed gamma rays above 398 TeV do not point back to any known TeV gamma-ray objects, but are ubiquitously spread over the galactic disk [9]. These spatially spread gamma rays are thought to have been produced by the interaction of cosmic-ray protons with the interstellar gas in our galaxy. the measured fluxes in the UHE region [9] are in reasonable agreement with a recent model [10] based on the hadronic cosmic-ray interactions, where UHE diffuse galactic gamma rays of electron origin is estimated to be negligible compared with those of cosmic-ray origin.

These arguments provide the first compelling evidence that cosmic rays, not electrons, were/are accelerated to PeV energies in our galaxy. This gives conclusive evidence for existence of cosmic-ray PeVatrons in the past and/or present galaxy. The existence of PeVatrons in our galaxy has been the subject of controversy for decades and is verified by this work. This work is also the first experimental proof of theoretical models that cosmic rays accelerated up to the "Knee" energy region are trapped by the magnetic field in our galaxy, forming a pool of cosmic rays. In addition, four events out of the 23 gamma-ray-like events located within $|b| < 10°$ above 398 TeV concentrate in the Cygnus Cocoon region (around $l = 80°$, $b = +1°$, which is a very promising candidate for a PeVatron [7, 8, 11]. This work provides further strong evidence that the Cygnus Cocoon is a cosmic-ray source Pevatron.

LHAASO recently reported the galactic diffuse gamma-ray flux[12] which is roughly a half of the flux observed by the Tibet ASγ experiment. However, as the LHAASO analysis excluded many regions in the Galactic plane, where there are many gamma-ray sources. the fluxes measured by the Tibet ASγ and LHAASO are difficult to be directly compared.

Meanwhile, IceCube succeeded in detection of galactic diffuse neutrinos in the 10 TeV region[13] around the 4.5 σ level without masking the Galactic plane, which should be compared with the sub-PeV gamma-ray flux of comic-ray origin by the Tibet ASγ experiment. The IceCube neutrino flux in the 10 TeV region smoothly connects with the Tibet ASγ sub-PeV gamma-ray flux, assuming the π^0 model[13], confirming the Tibet ASγ sub-PeV gamma rays along the Galactic plane are of cosmic-ray origin.

As for sub-PeV gamma-ray point (extended) sources, we reported Crab[1] in 2019 (at ICRC2019 as well), G106.3+2.7[14], Cygnus OB1 and OB2 regions[15] in 2021 (at ICRC2021 as well). Based on the data (roughly two live years) from 2014 and 2017, we reported[16] a sub-Pev gamma-ray source in the HESS J1843-033[17] region in 2022. The new gamma-ray source is named TASG J1844-038 detected above 25 TeV with a 6.2 σ level, as shown in Fig. 1.

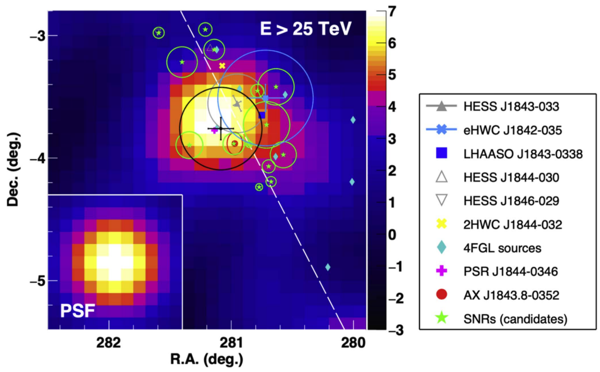

Figure 1: Cited from Ref.[16]. Significance map of the region of interest smoothed with the point-spread-function (PSF) radius of the experiment. The position with the statistical errors of TASG J1844-038 is shown with the black cross and the extension with the black circle. The white dashed line shows the Galactic Plane. The symbols and the circles with different colors indicate the positions and the extensions of nearby celestial sources shown in the right legend. The lower-left inset shows the PSF.

The position of which is consistent with HESS J1843-033, eHWC J1842-035, and LHAASO J1843-0338.

We measure the TASG J1844-038 gamma-ray energy spectrum in 25 - 130 TeV for the first time, as shown in Fig. 2.

It connects smoothly with that of HESS J1843-033 and is consistent with those of eHWC J1842-035 and LHAASO J1843-0338 at 56 and 100 TeV, respectively. The analysis of the combined gamma-ray spectra between the H.E.S.S., LHAASO, and TASG sources suggests a cutoff energy around 50 TeV. The association of the observed gamma rays with a nearby supernova remnant SNR G28.6-0.1 is discussed. we propose that cosmic rays accelerated by SNR G28.6-0.1 up

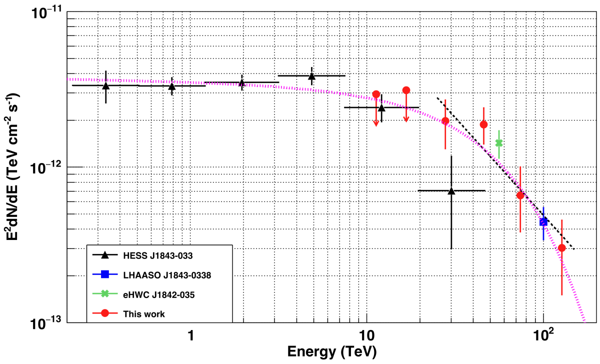

Figure 2: Cited from Ref.[16]. Energy spectra of TASG J1844-038 (red) and nearby gamma-ray sources[17],[5],[6]. The error bars are statistical and the downward arrows indicate the 95 % upper limits. The black dotted line is the best-fit PL function to our result, and the magenta short-dotted curve is the best-fit ECPL function (1) to the combined spectra between HESS, LHAASO, and this work. The flux of eHWC J1842-035 is our calculation from the published integral flux above 56 TeV[5].

approximately to 500 TeV generate the observed gamma rays from the collisions with the ambient gas found in the analysis.

2. Cosmic-ray enery spectrum

The hybrid experiment of the Tibet air shower array and muon detector array started in 2014. This study analyzed data observed during twelve days in 2014. Figure 3 shows an intensity map of the observed events taken during the twelve days. The horizontal axis shows the sum of the charged particle number density (log(Σ ρ)) measured by the Tibet air shower array, and the vertical axis stands for the number of muons (log (Σ μ)) in the shower measured by the muon detector array. To select proton-like events, we divide the data in the figure into six bins of Σ ρ ranging from $10^{2.6}$ to $10^{3.8}$ and examine the distribution of muons in each bin.

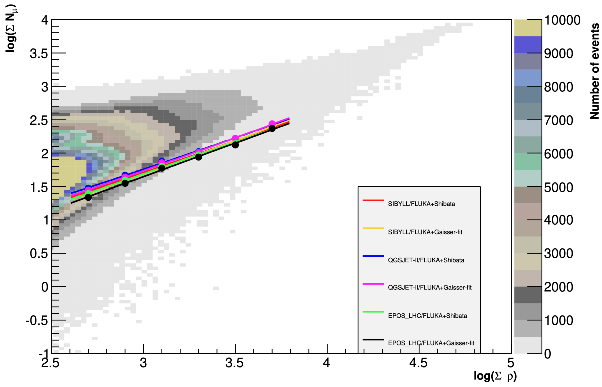

Figure 3: Cited from Ref.[18]. Event intensity map with log (Σ ρ) on the horizontal axis and log (Σ μ) on the vertical axis.

The dots in Fig. 3 shows the cut values keeping 90 % proton purity in each bin, and the solid lines are the fitted curves. The red dots shows cut values determined by simulations using the SIBYLL and FLUKA interaction model with the Shibata's composition model[19]. The shape of the ΣN_μ distribution depends on the interaction and composition models; thus, the value of the cut is different for each model. In Fig. 3, the orange dots, blue dots, purples dots, green dots, and black dots are cut values using SIBYLL/FLUKA+Gaisser-fit model, QGSJETII/FLUKA+Shibata model, QGSJET-II/FLUKA+Gaisser-fit model, EPOS_LHC/FLUKA+Shibata model, and EPOS_LHC/FLUKA+Gaisser-fit model. We define events with ΣN_μ smaller than these curves as proton-like events.

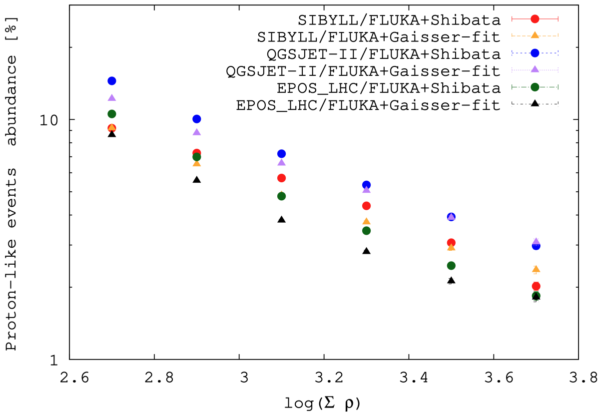

Figure 4: Cited from Ref.[18]. Proton-like shower abundance to whole well-reconstructed showers as a function of log ($\Sigma\ \rho$) for each model when purity is 90 %.

The abundances of proton-like events to whole well-reconstructed events at each $\Sigma\ \rho$ bin is shown in Fig. 4. The abundance including the model dependence, is 9.1 % - 14.5 % and 1.8 % - 3.1 % at about log ($\Sigma\ \rho$) = 2.7 and log ($\Sigma\ \rho$) = 3.7, respectively.

This method will enable us to measure the cosmic-ray proton energy spectrum in the hundred TeV region.

3. Cosmic-ray anisotropy

The distribution of arrival directions of TeV cosmic rays is known to have small anisotropy with amplitudes of ~0.1 %. We use the intensity-mapping method based on Liouville's theorem for the modeling of the TeV cosmic-ray anisotropy[20], as is shown in Fig. 5. The data employed in the analysis was taken from November 1999 to May 2010. we use the HEALPix algorithm[21] with $N_{\rm side}$ = 16, which divides the sky in our field of view (-20° < decl. < 80°) in 2056 pixels, each of which has an approximate size of 3.7° × 3.7°.

The experimental results from the Tibet ASγ experiment and the calculation of cosmic-ray trajectories in an MHD model heliosphere indicate that the relative intensity distibution of cosmic rays at the outer boundary of the heliosphere contains small-scale ansiotropic features with angular scales of smaller than ~10 %, which seems not to be realistic. A possible problem would be that the MHD model heliosphere used in this analysis is a single snapshot of the positive polarity phase of a solar cycle, while the experimental data covers ten years during the negative polarity phase of the 23rd solar cycle. In order to improve our intensity-mapping method, it would be necessary to have multiple snapshots of the MHD model heliosphere corresponding to the negative polarity phase, perform the intensity-mapping for each of the snapshots and take the average of the results.

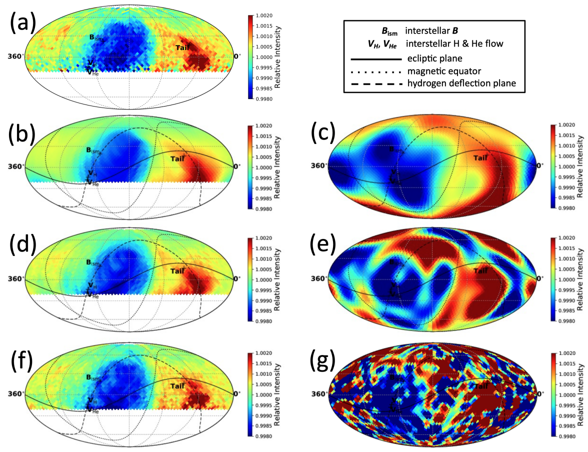

Figure 5: Cited from Ref.[20]. Panel (a) shows the experimental data. Panels (b), (d), (f) are the best-fit model relative intensity distributions at the Earth when we take the outer boundaries at distances of 630 AU, 1580 AU and 3980 AU from the Sun, respectively. Panels (c), (e), (g) are the best-fit model relative intensity distributions at the outer boundaries at distances of 630 AU, 1580 AU and 3980 AU from the Sun, respectively.

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