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Measurement of very-high-energy diffuse gamma-ray emission from $|b| < 5°$ of the Galactic plane with LHAASO-WCDA

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Galactic diffuse gamma ray emission (GDE) is introduced by the galactic cosmic rays (CR) interacting with the interstellar medium (ISM) and radiation fields (ISRF). The GDE is a very important probe of CR propagation and interaction. Different from the measurements of CR particles in the local vicinity, the GDE enables a direct measurement of CR distribution in the Milky Way, and can thus provide much more important information of the production and propagation of CRs. LHAASO-WCDA, with an large area of 78000 m^2, has an excellent ability to study VHE gamma-ray astronomy and GDE. In this proceeding, method of background estimation and some techniques to reduce the contaminant of resolved gamma-ray sources are briefly introduced. At last, diffuse emissions from the inner ($15° < l < 125°$, $|b| < 5°$) and outer ($125° < l < 235°$, $|b| < 5°$) Galactic plane are detected with 27.9σ and 11.9σ significance, respectively.

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1. Introduction

One of the most important unresolved problems in astrophysics is the origin and propagation of cosmic rays (CRs). The diffuse Galactic γ-ray emission provides a determination of the spatial distribution of CRs throughout the Galaxy, in contrast to direct observations of the energy spectra and anisotropies of CRs in the local region. As a result, it can offer considerably more significant information about production and propagation of CRs. The decay of neutral pions caused by inelastic collisions between CR nuclei and the interstellar medium (ISM), the inverse Compton scattering (ICS) of CR $e^{\pm}$ off the interstellar radiation field (ISRF), and the bremsstrahlung radiation of $e^{\pm}$ in the ISM are three major mechanisms that are thought to be responsible for the production of diffuse gamma-rays[1–3].

Space detectors have measured the all-sky diffuse emission at energies below 1 TeV[4–7]. Only a few ground-based investigations in certain locations of the Galactic plane were successful in detecting the diffuse emission at higher energies[8–11]. The recent measurements of the diffuse emission from 1 GeV to 500 GeV by Fermi-LAT [12], and the result with energies between 10 TeV and 1 PeV was reported by the LHAASO-KM2A[13]. High-precision measurements of the diffuse emission in the very-high-energy (VHE) to ultra-high-energy (UHE) domain are crucial to understanding the origin and propagation of CRs, particularly the physical origin of the new spectral features of CR nuclei by recent direct measurements [14, 15].

2. The LHAASO Experiment

The Large High Altitude Air Shower Observatory (LHAASO [16]) is a multi-component facility, located at an altitude of 4,410 meters in Haizi Mountain, Daocheng, Sichuan province, P.R. China. It is designed to detect air showers induced by cosmic-ray particles with energies ranging from a few tens of GeV to a few EeV. The whole detector array for LHAASO was installed and the scientific operation was launched in July 2021. LHAASO is projected to provide breakthrough insights into astroparticle physics as the most sensitive detector for UHE γ-rays and CRs, considerably furthering the study of CR physics, γ-ray astronomy, and new physics[19–23].

The Water Cherenkov Detector Array (WCDA) is a major component of LHAASO, which is primarily tasked with surveying the northern sky for very-high-energy (VHE) gamma ray sources [24, 25]. The whole WCDA, covering 78,000 m^2 detection area, contains 350,000 tons of purified water. It consists of 3 large pools, two of which have areas of 150 m$\times$ 150 m, and one of 300 m $\times$110 m. Each pool is subdivided into cells with area of 5 m$\times$ 5 m, separated by black plastic curtains to prevent any cross-talk of Cherenkov light between cells. In each cell, there are 2 photomultiplier tubes (PMTs) deployed at the bottom, facing upwards with an effective water depth of 4 m or 3.5 m above the photo-cathode. In this study, used the data recorded by WCDA, We report the measurements of the diffuse emission from the Galactic plane in energy range, from sub-TeV to 20 TeV.

3. Data Analysis

3.1 Monte Carlo Simulation

In this simulation, the air shower events are generated by CORSIKA v75000 [26]. The QGSJET-II model [27] and FLUKA libraries are used for high energy hadronic interactions and for interaction cross-section in low energy regions, respectively. The loss of the shower information is avoided by setting the kinetic energy cut to lower values than Cherenkov production threshold in the water for secondary particles in CORSIKA, that is, 50 MeV for hadrons and muons and 0.3 MeV for pions, photons and electrons [28]. The detector is supposed to be built at an altitude of 4410 m asl, and geomagnetic field components are set to 34.5 μT and 35.0 μT for north and downward vertical components of geomagnetic field respectively. Twenty-six different primary cosmic ray nuclei are used in simulation. The primary energy is sampled in the range from GeV to PeV, divided into several different energy ranges, at zenith angles $0° - 70°$, and uniformed azimuth angle $0° - 360°$.

The GEANT4 toolkit with v4.10.00 [29] version is employed to track the secondary particles of shower and their productions in the detector, where the PMT models are taken from GenericLAND software library [30]. The so-called G4WCDA programe which is based on the Geant4 is used to consider the detector geometry, particle interaction with materials in the WCDA detectors. The realistic experimental hall including the columns, beams and roof materials are all taken into account properly in this code.

3.2 Data

The full-array setup was used to get the data shown here for the WCDA from March 5th 2021 to March 31th 2023. For each PMT, a hit is formed with the threshold of 1/3 photoelectron (PE) for an 8-inch PMT, and 1 PE for a 20-inch MCP-PMT. By requiring at least 30 PMTs to fire concurrently over 12 × 12 PMT arrays within a window of 250 ns, a trigger algorithm was put into place to record CR air showers. Data quality tests based on the DAQ data status and reconstruction characteristics were carried out to guarantee a trustworthy data sample. Around 686 days of total effective live time were employed for the data analysis, with a trigger frequency of 35 kHz. More details about the array and the reconstruction can be found in [25]. The whole Galactic plane with Galactic latitudes within ±5° in the field-of-view of LHAASO is adopted as our region of interest (ROI). We further divide the analysis region into two parts, the inner Galaxy region ($|b| < 5°$, $15° < l < 125°$) and outer Galaxy region ($|b| < 5°$, $125° < l < 235°$), for detailed studies.

3.3 Background Estimation

In this study, the "direct integral method" [32] was used to estimate the cosmic ray background. This method assumes that the collecting efficiency's spatial distribution in the detector coordinates remains stable over a short period. The background is obtained through the direct convolution of the total event with the efficiency distribution.

Specifically, a time step of 4 hours were selected, and at each step, events that arrive within ±5 hours were used to calculate the spatial distribution. This long time window may result in spurious large-scale structures of the background, which need to be corrected during the analysis.

To reduce the impacts of known sources to the background estimate, we mask out relevant sky regions when calculating the background. The events within the regions of Galactic plane and resolved gamma-ray sources are excluded to estimate the background which is dominated by the residual CRs. The Galactic plane with latitude $|b| \leq 10°$ for declination $\delta \leq 50°$ and $|b| \leq 5°$ for $\delta > 50°$ was also masked. A smaller mask region for high declination regions is to ensure sufficient statistics left for an accurate background estimate.

3.4 Influence of Resolved Sources

The Galactic plane is a large complex region with many sources. To measure properly the diffuse Galactic emission, the contribution from point-like and extended sources in the WCDA catalog [33] and others detected by other experiments as compiled in TeVCat [34] should be excluded. To avoid contamination from resolved sources, we apply a mask with a radius of $R_{\rm mask} = n \cdot \sigma$ around each source. The constant factor n is chosen to balance the source contamination and the residual sky area and σ is the combined Gaussian width of the point spread function (PSF) of WCDA and the source extension. Here, We used $n = 2.5$ and $\sigma = \sqrt{\sigma^2_{\rm psf} + \sigma^2_{\rm ext}}$. Exceptions are made for particularly large sources, such as the Cygnus cocoon and Geminga with a mask radius of 6°, and Monogem with a mask radius of 8°.

The test statistic (TS) is used to evaluate the significance of the diffuse emission, defined by $TS = 2\ln(\mathcal{L}_{s+b}/\mathcal{L}_b)$, where $\mathcal{L}_{s+b}$ and $\mathcal{L}_b$ represent the likelihoods for the signal plus background hypothesis (H_1) and the background only hypothesis (H_0), respectively. The spectral energy distribution(SED) of the diffuse gamma-ray emission is calculated using the forward-folding method, assuming that the energy spectrum follows a single power-law distribution: $\phi(E) = \phi_0\,(E/E_0)^{-\alpha}$, where $E_0 = 3$ TeV is the pivot energy. The energy spectrum parameters ϕ_0 and α can be obtained by fitting the maximum likelihood values.

4. Results

The LHAASO-WCDA significance maps of the two sky regions after masking detected sources are shown in Fig. 1. The total significance of the inner (outer) Galaxy region is 27.9σ (11.9σ). No significant point-like sources are present in the significance maps after the mask, except for some hot spots, which need more data to confirm whether they are point-like sources or diffuse emissions.

From Fig. 1 we can see that considerable regions along the innermost Galactic disk are masked for the inner Galaxy region. We fit the measured spectrum using a power-law function, finding that the index is $-2.64 \pm 0.04_{\rm stat}$ for the inner Galaxy region and $-2.60 \pm 0.11_{\rm stat}$ for the outer Galaxy region. Possible spectral structures deviating from power-laws are not significant, and more data statistics are needed to further address such issues.

5. Discussion

Using the LHAASO-WCDA data, we present measurements of the diffuse gamma-ray emission in the VHE from sub-TeV to ~ 20 TeV from the Galactic plane. The inner Galaxy and the outer Galaxy regions are examined in the galactic plane as two sky regions (Fig. 1). We find considerable diffuse emission above TeV after masking the sources, with significances of with 27.9σ and 11.9σ for the two regions, respectively. A power-law can well describe the spectra in both the inner and outer regions with spectral indices of -2.64 and -2.60. The SED are consistent with Fermi-LAT

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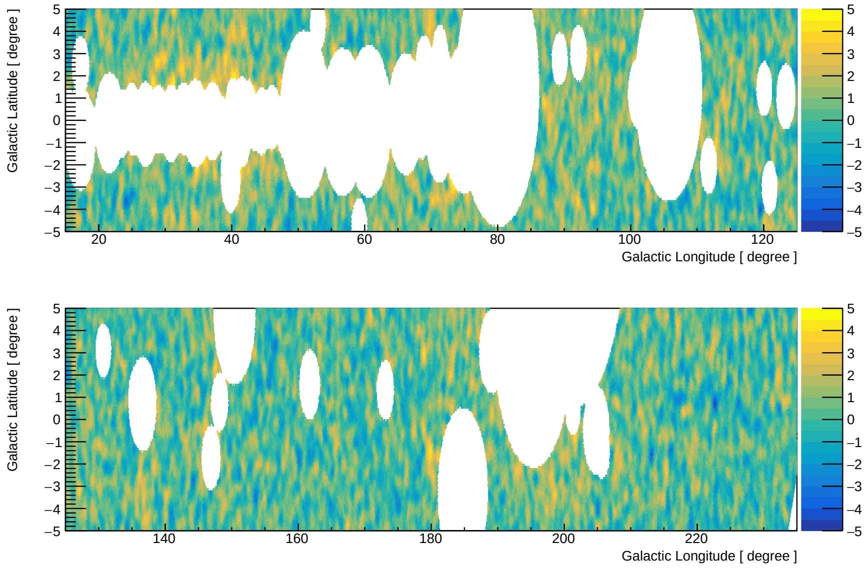

Figure 1: The significance maps in Galactic coordinate of the inner Galaxy region (top panel) and outer Galaxy region (bottom panel)) above TeV after masking the resolved WCDA and TeVCat sources.

and KM2A, however, there are some subtle structures and differences. In next analysis, there will be a consistent masking area, the same analysis strategy applied. Further understanding of the diffuse emission is expected to be achieved with the accumulation of more data by LHAASO.

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