Searching for neutrino signals correlated with LHAASO diffuse Galactic emission

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The diffuse Galactic $\gamma$-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 $\gamma$-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 $\gamma$-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 $d\phi_\nu/dE_\nu = 1.27 \times 10^{-14} (E_\nu/25\text{TeV})^{-2.99} \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$ for the diffuse $\gamma$-ray flux map with a 1.5$\sigma$ significance cut.
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 ($\pi^0$) decay into $\gamma$-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 $\gamma$-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 ($\pi^0$-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 $\pi^0$-decay $\gamma$-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 ($4.5\sigma$) 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 $\pi^0$-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 $4.1\sigma$[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 km², is optimized for detecting γ-rays with energies ranging from 10 TeV to a few PeV [24]. Located at a latitude of ~ 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 ($15^\circ < l < 125^\circ$, $|b| < 5^\circ$) and the outer Galaxy region ($125^\circ < l < 235^\circ$, $|b| < 5^\circ$). The spectrum of the diffuse emission are fitted with a power-law function $d\phi/dE = \phi_0(E/50 \text{ TeV})^{-\gamma}$, characterized by a spectral index of $\gamma = 2.99$.

In this study, we use the diffuse γ-rays flux map of the Galactic plane ($15^\circ < l < 235^\circ$, $|b| < 5^\circ$) 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 $0.5\sigma$, $1\sigma$, $1.5\sigma$, and $2\sigma$ 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 ($15^\circ < l < 235^\circ$, $|b| < 5^\circ$) 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
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\[ L(n_s, \gamma) = \prod_{i=1}^{N} \left( \frac{n_s}{N} S_i(x_i, \sigma_i, E_i; \gamma) + \tilde{D}_i(sin\delta_i, E_i) - \frac{n_s}{N} \tilde{S}_i(sin\delta_i, E_i) \right) \]  

(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), \( \tilde{D}_i \) is the scrambled background PDF estimated from data, and \( \tilde{S}_i \) 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 \( \gamma \)-rays below 100 TeV, the \( \gamma \)-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 \( \gamma \)-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 \( \gamma \)-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 \( \gamma \)-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.

<table>
<thead>
<tr>
<th>Spatial Template</th>
<th>( \hat{n}_s )</th>
<th>Upper Limit</th>
<th>( \phi_{90%}^{\text{observed}}/\phi_{90%}^{\text{theoretical}} )</th>
<th>Pretrial p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux map (0.5( \sigma ))</td>
<td>233.8</td>
<td>1.17 ( \times 10^{-14} )</td>
<td>123.9%</td>
<td>0.076</td>
</tr>
<tr>
<td>Flux map (1.0( \sigma ))</td>
<td>257.2</td>
<td>1.22 ( \times 10^{-14} )</td>
<td>146.9%</td>
<td>0.058</td>
</tr>
<tr>
<td>Flux map (1.5( \sigma ))</td>
<td>285.2</td>
<td>1.27 ( \times 10^{-14} )</td>
<td>186.0%</td>
<td>0.038</td>
</tr>
<tr>
<td>Flux map (2.0( \sigma ))</td>
<td>239.2</td>
<td>1.08 ( \times 10^{-14} )</td>
<td>217.5%</td>
<td>0.044</td>
</tr>
</tbody>
</table>

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 \( d\phi_{\nu}\nu_\mu/dE_\nu = \phi_{90\%} \cdot (E_\nu/25 \text{ TeV})^{-1.99}\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1} \) for the power-law neutrino spectrum converted from the \( \gamma \)-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].
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.

<table>
<thead>
<tr>
<th>Spatial Template</th>
<th>$\tilde{n}_s$</th>
<th>Upper Limit $\phi_{90%}$</th>
<th>Pretrial p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform map (with mask)</td>
<td>131.9</td>
<td>$1.01 \times 10^{-14}$</td>
<td>0.226</td>
</tr>
<tr>
<td>Gas template (with mask)</td>
<td>184.1</td>
<td>$1.12 \times 10^{-14}$</td>
<td>0.155</td>
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<tr>
<td>Gas template</td>
<td>244.3</td>
<td>$1.25 \times 10^{-14}$</td>
<td>0.085</td>
</tr>
</tbody>
</table>

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

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