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Constraining the Neutrino Flux of GRB 221009A with LHAASO Horizontal Events

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The study of cosmic neutrinos with energy $E_\nu \geq 10^{14} eV$ is one of the most important and challenging tasks in multi-messenger astrophysics. Detectors must operate in well shielded laboratories. An alternative is provided by the observation of Horizontal Air Showers (HAS, i.e. showers with a zenith angle $\geq 75°$) induced by neutrinos. With this technique the background of showers induced by cosmic rays is heavily reduced due to the large atmospheric depth and by the exponential attenuation of the shower electromagnetic component. In this contribution we discuss the HAS detection toward the bright GRB 221009A by the LHAASO-KM2A detector showing the expected differences of neutrino-induced events with surviving showers produced by cosmic rays. We introduce a preliminary selection to reject the background and report on a search for ν_e-induced HAS ($\theta \geq 75°$) in temporal coincidence with the prompt phase of GRB 221009A.

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1. Introduction

Observing neutrinos can introduce a fresh perspective on the universe by revealing hidden regions obstructed by massive objects. The astronomical neutrinos in the energy range from 100 TeV to sub-PeV generated by gamma-ray bursts (GRB) via $p\gamma$ interaction have been discussed in [1]. Neutrinos can escape directly from the core of a GRB without being affected by high-energy radiation, so neutrinos carry important information about the physical processes inside the GRB. The propagation speed of neutrinos, unimpeded by electromagnetic interactions, is almost equal to the speed of light. Therefore, neutrino detection can provide accurate direction and position information for studying the cosmic distribution of GRBs.

Recently, a bright GRB has been observed on 9 Oct 2022, named GRB 221009A. IceCube Observatory has set upper limits on neutrino flux in [2].

Several ground-based cosmic-ray experiments have searched for neutrinos. IceCube Neutrino Observatory has already collected neutrino events for over 10 years. MAGIC attempts to search neutrinos from events close to the horizon [3]. HAWC used Orizaba Volcano as a massive target for neutrino interactions [4]. The Pierre Auger Observatory analyzed two types of neutrino-induced showers: interacting in the deep atmosphere for any flavor, and charge-current interacting in Earth's crust [5].

The 1.3 km² array (KM2A) is a vital component of the LHAASO, consisting of electromagnetic detectors (EDs) and muon detectors (MDs)[6]. KM2A possesses an excellent capability to distinguish between muons and electromagnetic particles in a shower, enabling it to effectively differentiate electromagnetic cascades from hadronic ones. In this work, we search neutrino candidates in horizontal air showers (HAS) detected by KM2A. In the observational window, with a zenith angle larger than 75°, we can significantly decrease the cosmic ray background.

This article is organized as follows. In section 2, we discuss the characteristics of HAS and the difference between neutrino and cosmic rays. The results obtained with a full MC simulation of neutrino events in KM2A array are shown in section 3. Then we introduce the selection and identification criteria to identify neutrino candidate events with KM2A. In section 4, we calculate the exposure of KM2A and give the neutrino flux upper limit for GRB221009A. The conclusion is given in section 5.

2. Horizontal Air Showers

The altitude of the first interaction point in showers induced by protons or other nuclear particles is nearly 30 km. The slant depth from the first interaction point to the observation level is 2275 g/cm^2 for the zenith angle 75° and 15462 g/cm^2 for 89°. After traversing such a vast distance, the electromagnetic component is completely absorbed in the atmosphere. When showers induced by cosmic rays arrive at the observation level, secondary particles are mainly composed of muons. The secondary muons experience deflection due to the influence of the geomagnetic field, resulting in a more dispersed particle distribution at the front face. Furthermore, cosmic rays with low primary energy are unlikely to trigger the detector array, leading to effective background reduction.

Unlike cosmic rays, neutrinos can interact in the deeper atmosphere due to their extremely small cross-section. The first interaction point of the shower induced by neutrino could be very

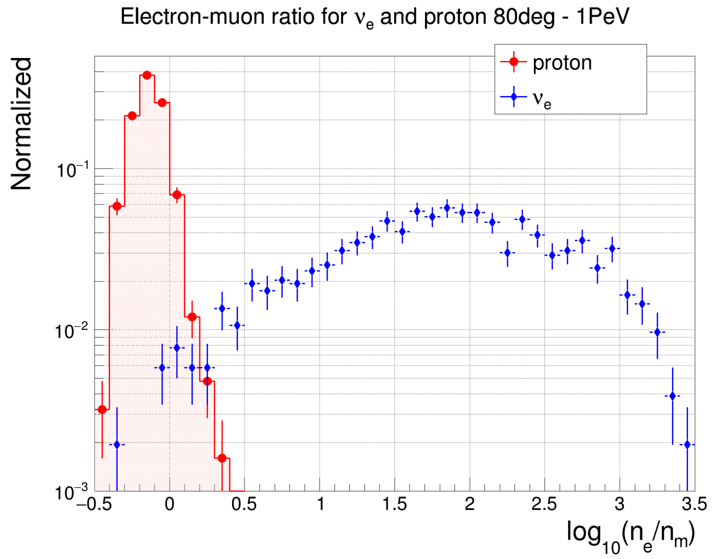

Figure 1: Distribution of the electron-muon ratio of secondary particles for ν_e (blue line) and proton (red line) HAS events with 1 PeV at the zenith angle 80° from Monte-Carlo simulation. n_e represents the number of secondary electrons, while n_m represents the number of secondary muons.

close to KM2A. According to MC simulations, the altitude of the first interaction point in showers produced by neutrinos able to trigger the array is in the range between 4.5 - 15 km when the zenith angle is greater than 75°. In this work, we mainly study the showers initiated by the charged current (CC) interaction of the electron neutrino. This interaction produces a new nuclear and an electron, leading to a shower composed of a high-energy electromagnetic component and a hadronic component. Neutrino showers are younger than cosmic ray ones, resulting in more rich electromagnetic component, with a more compact distribution on the shower plane.

The electron-to-muon ratio of secondary particles from showers with a zenith angle 80° is shown in Fig. 1. As expected, proton showers have a smaller electron-to-muon ratio, whereas neutrino showers exhibit a larger ratio. Therefore, in this analysis we will exploit this parameter to select neutrino candidate events.

3. Monte-Carlo Simulation

The full Monte Carlo simulation of neutrino events of KM2A is divided into two steps, extended air shower simulation and detector response simulation.

We used CORSIKA77410 to simulate the horizontal air showers induced by neutrinos [7]. The interaction model QGSJETII and FLUKA is chosen for high and low energy, respectively. In this study, we specifically focus on the CC interaction of electron neutrinos. We utilize the HERWIG code to calculate this initial interaction and to subsequently inject the resulting secondaries into CORSIKA for further simulation.

Due to the relatively low cross-sections of neutrinos, the first interaction points are almost uniformly distributed along the atmospheric path. Therefore, we randomly sample this altitude from 4.5 km to 15.0 km based on atmospheric density. Regarding the direction, the zenith angle

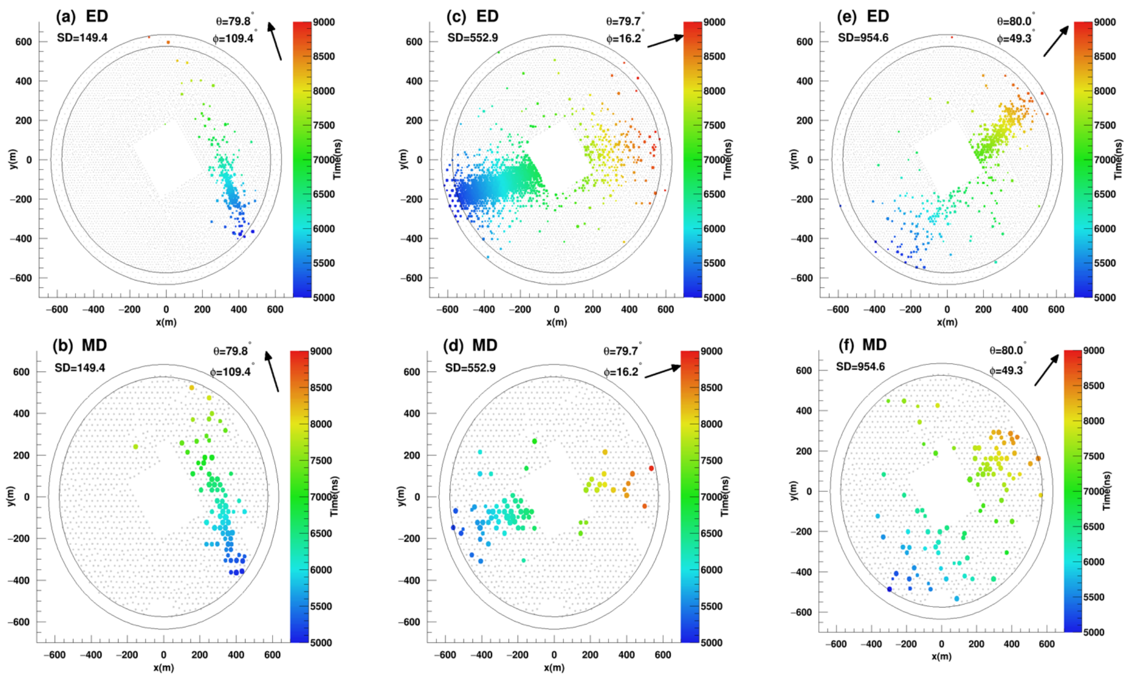

Figure 2: The plots a and b, c and d, e and f are the ED and MD footprints of the three ν_e simulated HAS events interacting at different altitudes. The primary energy is 1 PeV. SD is the slant depth, gcm^{-2}, θ is zenith angle and ϕ is azimuth angle.

is sampled on average between 75° and 89°, while the azimuth angle ranges from 0 to 360°. The primary energy of neutrinos spans from 10 TeV to 10 PeV, with an energy spectrum index of -2. When the energy exceeds 5 PeV, the thinning option of CORSIKA is applied.

The detector response process is simulated by GEANT4[8]. With the noise hit added, we required 20 EDs collected within a time window of 600 ns as the trigger threshold. Sampling area is a circle with a radius of 1 km centered around the center of LHAASO. Fig.2 shows the footprint of three 1 PeV typical neutrino events interacting at different altitudes on LHAASO.

We reconstructed the shower core position and the arrival direction of the simulated events using the centroid method and the cone fitting method, respectively [9]. For the neutrino events, the core resolution defined by 68% of events is 12.8 m, while the angular resolution is 0.51°, which is significantly better than the horizontal cosmic ray events.

4. Upper Limit of GRB 221009A

GRB 221009A was detected by the Fermi spacecraft on October 9, 2022, at 13:16:59.99 Universal Time (UT) [10]. It was located within the field of view of LHAASO at a zenith angle of 28.1°[11]. The GRB entered our observation window (75° < θ < 89°) at 16:54:06 on the same day and remained for 67 minutes. In this section, we will set upper limits for neutrino flux from this source with this 67-minute observation.

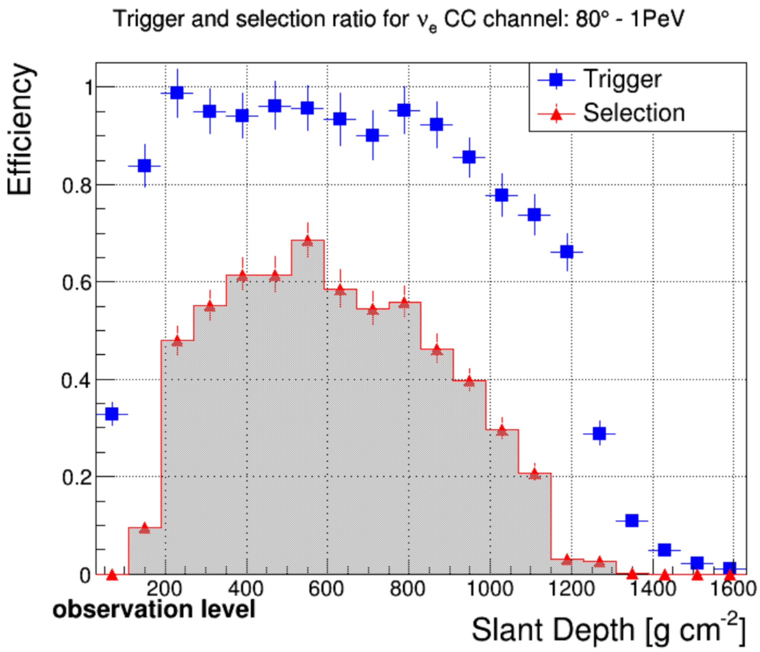

Figure 3: Taking MC simulation result of ν_e HAS events with energy 1 PeV at 80° as an example, we demonstrate the relationship between slant depth, trigger efficiency (blue line), and selection efficiency (red line).

4.1 Selection of Neutrino Showers

Using the simulation data presented in Section 3, we establish the criteria to select neutrino candidate events.

In this analysis, only the events with zenith angle $75° < \theta < 89°$ are considered. To mitigate the impact of edge effects of the azimuthal distribution, we preserve only well-reconstructed events with a core position at least 50 m away from the boundaries of the detector array. Compared to the vertical air shower signals, the HAS signals are more susceptible to noise contamination due to their broader time distribution. Therefore, we choose a more stringent N_{hit} criterion here to ensure the reconstruction quality of HAS. Specifically, we require a minimum of 120 hits in the event after noise filtering. This constraint eliminated a significant number of events with high interaction altitudes and low energy.

We define the selection rate as the ratio of the number of events that satisfy the criteria to the total number of events sampled. The trigger rate and selection rate for 1 PeV neutrino events at 80° are then plotted in Fig. 3 as a function of slant depth. For events with small slant depth, their first interaction points are close to the detector array. Consequently, the showers do not acquire sufficient material depth to attain a size large enough to trigger or meet the selection criteria. As for events with large slant depths, the rate decreases due to the attenuation of the electromagnetic component. Between 300g/cm^2 and 800g/cm^2, the trigger rate remains close to 1, and the selection rate hovers around 60%.

For ν_e horizontal air showers (HAS), the electromagnetic component is prominent. To discriminate between neutrino signal and cosmic-ray background, we utilize a discriminate parameter

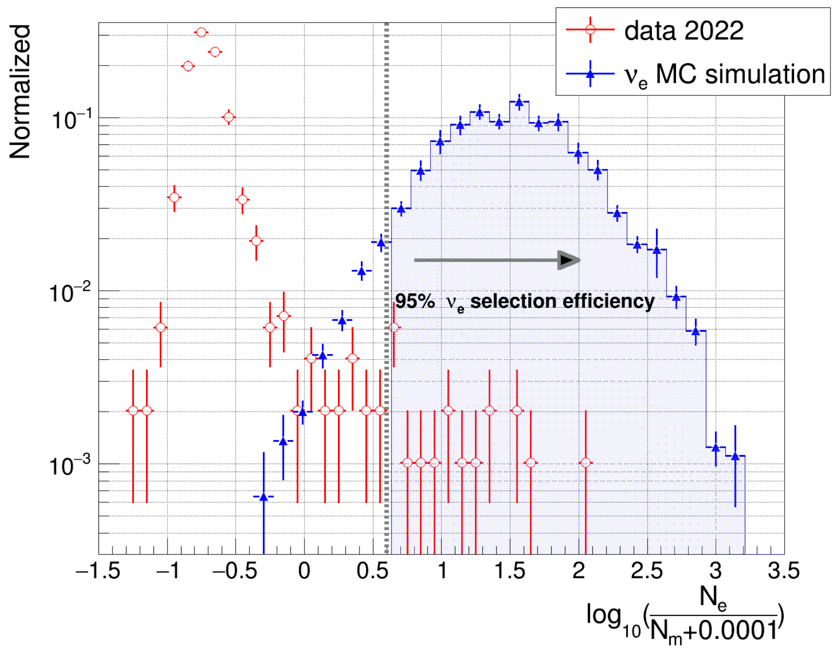

Figure 4: Distribution of identification parameter R for ν_e (blue line) and data (red line). Neutrino candidates are defined as events with R exceeding 0.6, containing 95% of the signal events.

R, following the expression

$$R \equiv \log\left(\frac{N_e}{N_m + 0.0001}\right), \tag{1}$$

, where N_e is the summation of secondary particles from ED hits within a distance of 200 m from the shower axis, while N_m is the summation of MD particles detected between 15 m and 200 m from the shower axis.

Fig.4 shows the discriminate parameter R for ν_e cosmic ray and neutrino HAS. Due to the low trigger rate of horizontal cosmic ray events, here we opt to use the data collected throughout the entire year of 2022 instead of the cosmic ray simulation data, which may exhibit large fluctuations. To contain 95% signal events, the criterion of the discriminate parameter is set to $R_{crit} = 0.6$, and the events with $R > R_{crit}$ will be considered a neutrino candidate. There are 18 neutrino candidates in the whole year of 2022, but none of them falls in the window of GRB 221009A.

4.2 Statistical Analysis

When the source transits our observation window, we can determine the expected number of neutrinos, N_{exp}, within a specific energy range

$$N_{exp} = \int \alpha E^{-2} \varepsilon(E,\theta)\varphi(E,h,\theta)\mathrm{d}h\mathrm{d}E\mathrm{d}t\mathrm{d}S. \tag{2}$$

The assumed neutrino flux intensity is αE^{-2}, where α represents a normalization factor. The collision occurrence rate, $\varphi(E,h,\theta)$ at altitude h and zenith angle θ with energy E, is determined by the charged-current (CC) cross-section[12] and the density of the atmosphere. The identification rate, $\varepsilon(E, \theta)$, is primarily influenced by the energy E and zenith angle θ for KM2A HAS events. This rate is obtained through MC simulation mentioned in section 3.

The sampling area, denoted as S, is a circular region with a radius of 1km. The energy range considered is from 100TeV to 10PeV, and the altitude integrals are calculated between 4.5km and 15km.

The Equi-zenith method is adopted to analyze the GRB 221009A horizontal event mentioned above, resulting in no signal or background detected. Employing the Feldman–Cousins approach, we obtained an upper limit on N_{exp} (2.44) at a confidence level of 90%[13]. The parameter α of the neutrino flux is constrained as follows $\alpha < 1.95\mathrm{GeVcm^{-2}s^{-1}}$

5. Conclusion

In this study, we have focused on the search for high-energy ν_e using the LHAASO-KM2A detector in the field of view at large zenith angles. The immense depth of the atmosphere leads to a significant reduction in cosmic ray background, especially its electromagnetic component. However, neutrinos behave differently as they can interact in the deep atmosphere, preserving the electromagnetic cascade. This distinction is illustrated in Fig. 1.

Through MC simulation, we have thoroughly investigated KM2A's capability to detect and identify ν_e HAS events. Furthermore, we have presented the footprints of three representative examples in Fig.2. Additionally, we have established filtering conditions, and the selection efficiency for ν_e with1 PeV at a zenith angle of 80° is depicted in Fig. 3.

In response to the lower characteristic interaction point for neutrinos, we utilize the parameter R, as defined in section 4.1, to differentiate ν_e events from cosmic ray background. We consider events with a parameter R exceeding 0.6 as potential ν_e candidates. In a large zenith angle range, we have observed the afterglow of GRB 221009A for 67 minutes without detecting any signal or background. Based on this observation, we determined an upper limit for the ν_e flux smaller than $1.95\,(E/1\mathrm{GeV})^{-2}\,\mathrm{GeV^{-1}cm^{-2}s^{-1}}$, in the energy range from 100TeV to 10PeV.

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