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Chapter 6 Multimessenger Physics*

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Abstract: Combining observations of multi-messengers help in boosting the sensitivity of astrophysical source searches, and probe various aspects of the source physics. In this chapter we discuss how LHAASO observations of very high energy (VHE) gamma rays in combination with telescopes for the other messengers can help in solving the origins of VHE neutrinos and galactic and extragalactic cosmic rays.

Keywords: Cosmic ray, gamma-ray, neutrino, LHAASO

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I. SEARCH FOR GALACTIC COSMIC-RAY PEVATRON SOURCE

There are many candidate sources of PeV cosmic rays in the Milky Way. Gamma-ray detection of these sources at the ultrahigh-energy band proves their potential of acceleration of PeV protons as particle accelerators. High-energy neutrino detection would serve as a smoking gun to identify that acceleration of PeV protons are indeed proceeding in these sources.

A. Introduction

Detection of the so-called 'knee' at ~ PeV in the cosmic ray proton spectrum implies that there are petaelectronvolt accelerators ('PeVatron') residing in our Galaxy. Power-law spectra of gamma-rays extending to at least several tens of TeV without a cut-off has been suggested as the identifier of such kind of powerful proton accelerators. However, despite of a large amount of cosmic ray accelerators has been found at TeV in our Galaxy, none of them has shown the unequivocal feature of PeVatron, except that HESS experiment has discovered a likely existence of proton PeVatron within the central 10 parsecs of the Galaxy at roughly 2σ confidence level [1]. LHAASO has a good sensitivity for gamma-ray with > 10 TeV, in particular, reaching an unprecedented level around 100 TeV and hence can serve as an efficient PeVatron detector. Among 78 VHE sources in the HESS Galactic Plane Survey catalog [2], 21 of them are in the field of view of LHAASO. By extrapolating the spectrum of these sources with the best-fitting spectral model (power-law model or exponential cutoff power-law model) to 1 PeV, 19 of them is beyond the 5σ detection limit of LHAASO with one-year observation. There are many more PeVatron candidates beyond the field of view of HESS but in that of LHAASO. For example, the star-forming region Cygnus Cocoon is one of the proposed cosmic-ray accelerator [3]. Gamma-ray emission from this region has been detected by Fermi-LAT [4], Milagro [5], ARGO-YBJ [6], Veritas [7] and HAWC [8] in GeV–TeV band with a quite complex morphology, implying contributions from multiple sources. In fact, some of these sources have already been detected by half of LHAASO-KM2A at the ultrahigh-energy (UHE) gamma-ray band ($E \geq 100$ TeV, [9]). Among 12 UHE gamma-ray sources detected by LHAASO, most of them are associated with supernova remnants (SNRs), pulsar wind nebulae (PWNe) and star-forming regions, implying these

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sources as proton PeVatron candidates.

To put it shortly, LHAASO has revealed many sources as potential proton PeVatrons and is promising to discover more new PeVatron candidates in the future. Based on the current observation, however, it is difficult to differentiate the hadronic origin and the leptonic origin for most of LHAASO detected sources. High-energy neutrinos from these sources would be a smoking gun for the hadronic origin, since high-energy gamma rays and neutrinos are produced associately in hadronic interactions of cosmic rays with comparable flux. However, no astrophysical neutrino sources had been clearly identified by IceCube yet and hence only neutrino flux upper limit are available [10]. Even so, the upper limits can already put interesting constraints on the origin of UHE gamma rays of some LHAASO sources [11]. We note that using the LHAASO measured spectrum as a prior in IceCube's analysis may enhance the post-trial significance of the sources and in turn leads to more stringent neutrino flux upper limits.

B. Supernova Remnants

SNRs, especially young SNRs with age less than one thousand years such as Tycho, Cas A and so on, are believed to be able to accelerate CRs up to PeV energies, and contribute to the Galactic CRs. The interaction between accelerated CRs and the surrounding matters would produce γ-rays and neutrinos. π^0 bumps are observed in the γ-ray spectra of SNRs W44 and IC443 as the indications of hadronic interactions [12]. Previous studies on the TeV gamma-ray emissions associated with SNRs W28, W41, W51C and CTB37A also suggested that these TeV emissions are possibly powered by the hadronic interactions. In particular, a middle-aged SNR G106.3+2.7 has been extensively studied in GeV band [13], TeV band [14–16], and X-ray band [17, 18]. Theoretical studies have also been carried out to investigate its possibility as a proton PeVatron [17, 19]. LHAASO's measurement extended its spectrum up to about 600 TeV. It is predicted that IceCube can detect 0.4 muon neutrinos above 50 TeV for the ten-year operation in the hadronic model. Future observation of LHAASO and IceCube (as well as the next-generation neutrino telescope) should be able to test the hadronic model.

C. Pulsar wind Nebulae

PWNe are also believed to be a kind of Galactic cosmic ray sources. The pulsar wind interacting with the ambient medium around a pulsar forms a terminal wind shock, which will accelerate particles to high energy. The accelerated CRs interact with matters or photons in the nebulae would produce gamma-rays and neutrinos. More than 30 PWNe have been detected at TeV energies. A stacking analysis to search for neutrino emission from 35 TeV PWNe using 9.5 years of all-sky IceCube data finds no significant correlation between PWNe and neutrinos [20]. Extended TeV γ-ray emission are detected from nearby sources Geminga pulsar and B0656+14 by HAWC [21]. More extended TeV images of PWNe might be discovered by LHAASO. The spectral features and the gamma-ray profiles of PWNe detected by the LHAASO would help IceCube to improve the neutrino searches. It is interesting to note that the latest observation of LHAASO on the Crab Nebula has extended its spectrum up to 1.1 PeV and reveal a possible hardening of its spectrum above several hundred TeV [22]. This might be interpreted as an additional hadronic component at the highest energies.

D. Star-forming Regions

Star-forming regions are factories of stars/star clusters, and usually associated with molecular clouds, such as W51A, W51B, Cygnus region, W49A and W43. The young OB star clusters, super bubbles supplied by supernova explosions or collective stellar winds, or SNRs/PWNe in the star-forming regions could accelerate CRs to high energy. The high energy CRs that are confined in the star-forming regions would interact with molecular clouds, and produce gamma-rays and neutrinos.

We assume that, in a star-forming region in the Galaxy, a PeV CR accelerator are accompanied with molecular clouds, and the accelerated PeV CRs escape from the accelerator and are confined in the molecular clouds with the total energy of $E_{\rm inj}$. Gamma-rays and neutrinos are produced via the interaction between CRs and molecular clouds. The corresponding extended sources might be observed with the gamma-ray and neutrino profiles following the distribution of the molecular clouds. The gamma-ray flux at the energy of 100 TeV is about $f_\gamma = \dfrac{1}{3} E_{\rm inj} n_{\rm H} \sigma_{pp}^{\rm inel} c/(4\pi D_{\rm L}^2)$, i.e.,

$$f_\gamma = 3\times 10^{-12}\ {\rm TeV\ cm^{-2}\ s^{-1}} \times \left(\frac{E_{\rm inj}}{10^{50}\ {\rm erg}}\right)\left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)\left(\frac{D_{\rm L}}{10\ {\rm kpc}}\right)^{-2} \tag{1}$$

where $\sigma_{pp}^{\rm inel} \simeq 50\,{\rm mb}$ is the approximated cross-section for inelastic pp collision [23], and $n_{\rm H}$ is the density of the molecular clouds. The muon neutrino flux at 50 TeV is about 10^{-12} TeV cm^{-2} s^{-1}$(n_{\rm H}/1\ {\rm cm^{-3}})$ for $E_{\rm inj} = 10^{50}$ erg and $D_{\rm L} = 10$ kpc, and the integrated counts of muon neutrinos for ten year operation of IceCube can be estimated to be $N_\mu = 4(A_{\rm eff}/1\ {\rm m^2})(E_{\rm inj}/10^{50}{\rm erg})(n_{\rm H}/1\ {\rm cm^{-3}})(D_{\rm L}/10\ {\rm kpc})^{-2}$. IceCube reported the results of searching for extended sources of neutrino emission with 7 years of IceCube data, with the discovery potential flux at 50% confidence level for the Northern Hemisphere about $\sim 10^{-12} - 10^{-11}$ TeV cm^{-2} s^{-1} [24]. Therefore, a PeVatron associated with molecular clouds in the Galactic star-forming region might be a possible extended gamma-ray source candidate for LHAASO, and also a possible extended neutrino source candidate for IceCube, depending on the total injected energy, the source distance, and the mass of molecular clouds. LHAASO's future discovery on new extended sources in the Galaxy will improve the discovery potential of IceCube.

E. Gamma-ray Binary System

In γ-ray binary systems, such as LS 5039, HESS J0632+057, and LS I+61°303 [25], particles might be accelerated to high energy via the pulsar wind interacting with the strong wind of massive star, the jet activities in micro-quasars, or relativistic outflow interacting with the ISM, and further produce gamma-rays and neutrinos. In particular, HAWC detected TeV emission above 25 TeV from the jet's lobe of microquasar SS433 [26], demonstrating that the binary system could be an efficient particle accelerator. The searches for time dependent neutrino sources with IceCube data from 2008 to 2012, find no significant time dependent point sources of neutrinos, but the most significant neutrino excess from the binary system HESS J0632+057 with pre-trial p-value of 0.087 [27]. Chances are that LHAASO would discover more nearby gamma-ray binaries, and provide a gamma-ray binary catalog for the IceCube to search for more neutrino sources.

II. FOLLOW-UP STUDY ON ICECUBE NEUTRINO SOURCES

The IceCube neutrino observatory is sending public real-time alerts on single muon neutrino-induced track events with a high probability of being of astrophysical origin. Since 2019, more than 40 neutrino singlet alerts located within LHAASO's field of view (FOV) were reported. If the source is nearby with no photon attenuation inside the source and along the propagation path, there is a high chance that LHAASO can observe high energy photons associated with the IceCube announced single muon neutrino alerts. Besides performing observations following up the IceCube neutrino alerts, LHAASO can also provide public alerts for the follow-up neutrino detections. What's more, LHAASO's observations on nearby blazars and starburst galaxies can provide more details on the nonthermal processes operating in the neutrino source candidates.

A. Introduction

The IceCube neutrino observatory, located under the Antarctic ice, is the largest neutrino detector to date. Since 2016, IceCube started to send public real-time alerts on single-muon neutrino-induced track events with a high probability of being of astrophysical origin, based on the real-time, online event reconstruction, through Astrophysical Multimessenger Observatory Network (AMON) and Gamma-ray Coordination Network (GCN) [28]. In 2019 June, the HESE (High Energy Starting Events) notices and EHE (Extremely High Energy) notices are replaced by so called "ICECUBE ASTROTRACK GOLD notices" and "BRONZE notices", with the rate about 12/ yr and 16/ yr, the chance of $> 50\%$ and $> 30\%$ to be astrophysical [29], and the position error of $0.2° - 0.75°$. Since 2019 September, more than 40 neutrino singlet alerts within LHAASO's field of view were reported. In addition to muon neutrino-induced event alerts, IceCube has a real-time program to search for muon-neutrino multiplets. In 2016, the IceCube real-time neutrino search identified a muon-neutrino multiplet, with no likely electromagnetic counterpart detected [30].

B. Follow-up Observations of the IceCube Neutrino Alerts

The large FOV, high duty cycle and high sensitivity make LHAASO a perfect detector on searching for very high energy gamma-ray transients or steady sources associated with the IceCube neutrino alerts. What's more, IceCube is more sensitive to sources in the Northern hemisphere, since events from the Southern hemisphere are highly contaminated by the muon backgrounds [31], and most of the LHAASO's FOV is in the Northern hemisphere. This fact also makes LHAASO a suitable detector to do the follow-up observations to the direction of the IceCube neutrino alerts. Since most of IceCube neutrino alerts locate to the direction of high galactic latitude, if they are of astrophysical origins, they are likely to be from extragalactic sources. Due to the extragalactic background light (EBL) absorption, the flux of $\gtrsim$10 TeV photons from sources with distance larger than a few Mpc will be suppressed. Therefore, the detection horizon of LHAASO KM2A is limited to be a few Mpc. The EBL absorption is weak for TeV photons from sources within a few hundred Mpc, thus, the LHAASO WCDA are able to detect photons from sources within a few hundred Mpc.

For steady neutrino sources, the duration of the neutrino emission at the source can be as high as the IceCube operation time. Let us denote the energy of a neutrino by $E_{\nu_\mu}^{\rm obs}$, the effective area of the IceCube by $A_{\rm eff}$, and the duration of neutrino emission at the source by T_ν. Assuming the neutrino spectrum $\dfrac{{\rm d}N_\nu}{{\rm d}E_\nu} \propto E_\nu^{-2}$ with $E_{\nu,\min} = 1$ TeV and $E_{\nu,\max} = 10\,{\rm PeV}$, the flux of a single muon neutrino-induced event is estimated as $E_{\nu_\mu}^2 {\rm d}N_{\nu_\mu}/{\rm d}E_{\nu_\mu} = E_{\nu_\mu}^{\rm obs}/(\ln(E_{\nu,\max}/E_{\nu,\min})A_{\rm eff}T_\nu)$, i.e.,

$$E_{\nu_\mu}^2 \frac{{\rm d}N_{\nu_\mu}}{{\rm d}E_{\nu_\mu}} \simeq 4\times 10^{-12}\ {\rm TeV\,cm^{-2}\,s^{-1}} \times\left(\frac{E_{\nu_\mu}^{\rm obs}}{100\ {\rm TeV}}\right)\left(\frac{A_{\rm eff}}{1\ {\rm m}^2}\right)^{-1}\left(\frac{T_\nu}{10\ {\rm yr}}\right)^{-1}. \quad (2)$$

Since the gamma ray flux is about 2 times larger than the muon neutrino flux considering the equipartition among the three neutrino flavors after their oscillations during the propagation, the gamma-ray flux at 100 TeV is about

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \sim 8\times10^{-16}\ \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1} \times\left(\frac{E_{\nu_\mu}^{\rm obs}}{100\ \mathrm{TeV}}\right)^{-1}\left(\frac{A_{\rm eff}}{1\ \mathrm{m}^2}\right)^{-1}\left(\frac{T_\nu}{10\ \mathrm{yr}}\right)^{-1}$$

if there is no photon attenuation within the source and along the propagation path. Therefore, if a single neutrino with energy about $E_{\nu_\mu}^{\rm obs}=100$ TeV is observed from a nearby steady source, the expected gamma-ray flux at 100 TeV with no absorption is larger than the sensitivity of LHAASO at 100 TeV for one year operation, as shown in Fig. 1. To be noticed here, the effective area of IceCube is a function of declination. Therefore, if there is no photon attenuation inside the source and along the propagation path, there is a high chance that LHAASO KM2A can observe high energy photons associated with

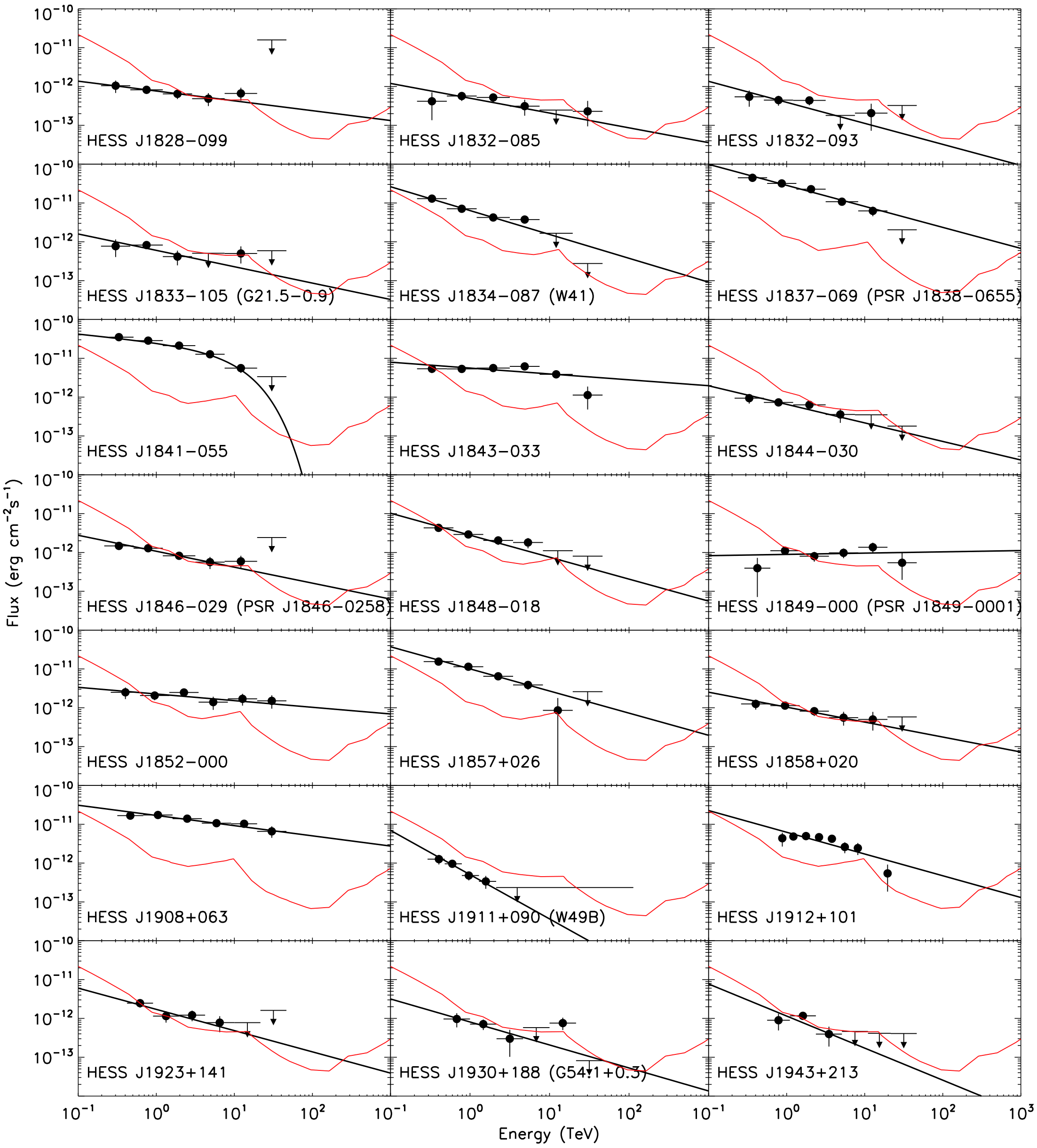

Fig. 1. (color online) 21 sources from HGPS catalogue that are in the field of view of LHAASO. Black data points are the measurement by HESS, and black curves show the best-fit spectrum model [2]. Red curves show the sensitivity of LHAASO for each source with one-year observation. The sensitivity is estimated by multiplying a factor of $\max(1,\theta_s/\theta_{\rm PSF})$ to the sensitivity for Crab, where θ_s is the angular size of the source measured by HESS while $\theta_{\rm PSF}$ is the size of PSF of LHAASO.

the IceCube announced single muon neutrino alerts and muon neutrino multiplets.

Besides performing observations following up the IceCube neutrino alerts, LHAASO can also provide public alerts for the follow-up neutrino detections. LHAASO are able to search for the hotspot with a cluster of events above the estimated cosmic-ray background level with an excess significance above 2.75 σ, and provide the information of the hotspot for the IceCube collaboration to search for neutrinos associated with the LHAASO hotspot temporally and spatially. Then, the IceCube and LHAASO collaborations can issue the IceCube LHAASO alert based on gamma rays and neutrino sub-threshold detections, similar to the IceCube HAWC alert. The combined analysis on the observed gamma-ray photons and neutrinos would help to improve the discovery potential of neutrino sources.

C. Blazars and Starburst Galaxies

Blazars and starburst galaxies are two major source candidates for the IceCube diffuse neutrino background.

Blazars are relativistic jets driven by supermassive black holes with directions aligned with the observer's line of sight. They have been proposed as the high-energy neutrino sources for decades [32– 35]. Ref. [36] found 11 significant neutrino flares using a sample of muon track neutrino events from 2012 April to 2017 May, associating with 10 AGN counterparts, including FSRQs, BL lac and radio galaxies. In addition, 9 blazars are summarized associated with single high-energy neutrino events, including both archival neutrino events and neutrino alert events [37].

One of the most promising high-energy neutrino candidates to date is blazar TXS 0506+056, which is detected in spatial and temporal coincidence with a ~ 300 TeV neutrino event IC-170922A at 3σ level during its flaring state [38]. A later analysis on the archival data revealed 13 ± 5 additional neutrino events from the same direction during about 4 months in 2014-2015 [39]. This may be an evidence of blazars as cosmic ray proton accelerators at least to ~ 10 PeV. If TXS 0506+056 is truly a neutrino emitter, it will be also a multi-TeV gamma-rays producer through the same hadronic interactions. However, due to the large distance of the blazar (at a redshift of about 0.34) to Earth, the produced multi-TeV gamma-ray photons will be severely absorbed during their propagation in the intergalactic space, even if the internal absorption due to the emission of the blazar itself is not important.

Nevertheless, it'd be worth monitoring the closest blazars, such as Mrk 421 and Mrk 501 with distance 126 Mpc and 157 Mpc away from Earth, respectively, at which distance the attenuation for multi-TeV flux is not very strong. Another interesting source in the field of view of LHAASO is the radio galaxy M87, which is considered as the misaligned counterpart of blazars. It was found associated with a short neutrino flare in 2016 of a duration about 3.9 minutes with a p-value of 1.91×10^{-3} [36]. Given the distance of M87 to be about 16.4 Mpc, the detection of 100 TeV gamma-ray photons is in principle possible, if the intrinsic flux is high and the internal absorption is not strong. Nevertheless, even if only upper limits of multi-TeV gamma-ray fluxes are obtained, the results may be useful to constrain the radiation model of blazars and relevant physical quantities, such as the size/location of the emitting region, particle acceleration capability and the composition of the jet.

Starburst galaxies are another major candidates of high-energy neutrino sources. Theoretical studies have shown that starburst galaxies are able to contribute to, at least a considerable fraction of, the diffuse neutrino background detected by IceCube (e.g. [40– 43]). In the ten-year search for steady point-like[1] neutrino sources by IceCube, the hottest spot with a post-trial significance of 2.9σ [10] is in the direction of a nearby starburst galaxy NGC 1068 (M77) (14.4 Mpc from Earth), which shows starburst activity and an active galactic nucleus.

There are some other nearby starburst galaxies located in the LHAASO's FOV. For example, M82 (also known as Cigar galaxy) is one of the closest starburst galaxies (3.5 Mpc) and is usually considered as a prototype of starburst galaxy. It has been observed by VERITAS [44] up to a few TeV with a power-law spectrum showing no clear cutoff. The TeV emission is believed to arise from the pp collision between cosmic rays in the galaxy and the interstellar medium (ISM), so high-energy neutrino emission from M82 is naturally expected. Although the IceCube has not found any neutrino excess in the direction of M82, the multi-TeV gamma-ray observation would help to determine the hadronic interaction efficiency in starburst galaxies at the energy regime interesting for high-energy neutrino astronomy.

III. HIGH-ENERGY NEUTRINOS AND GAMMA RAYS FROM CORE-COLLAPSE SUPERNOVAE

The interaction between the core-collapse supernova (CCSN) ejecta and the dense circumstellar medium (CSM) could generate the shock waves and then accelerate the cosmic rays beyond PeV energies. Multi-messenger signatures, e.g., the high-energy gamma-rays and the high-energy neutrino emission, could rise from the inelastic pp collision between the high-energy cosmic rays and the gas therein. Such high-energy gamma-rays from

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[1] Given different angular resolutions between IceCube and LHAASO, a point-like source viewed by IceCube could be an extended source viewed by LHAASO.

the interaction of the CCSN ejecta and the CSM could reach the sensitive energy range of LHAASO. The joint observations and studies of the simultaneous gamma-ray emission and neutrino emission could help us to find out the nature of CCSNe, e.g., the properties of the progenitor, the circumstellar environment, the acceleration of cosmic rays and so on.

A. Introduction

A high-density circumstellar wind environment in the immediate vicinity of the progenitor can be caused by the sustained mass-loss of the progenitor before the explosion of CCSNe, and after the explosion, the interaction of supernova ejecta with the optically thick wind could result in a bright, long-lived wind breakout (i.e., CSM breakout) event, which may also make the usual envelope breakout delay. There are increasing evidences that large mass loss episodes closely preceding the CCSN explosion are not uncommon. The early lightcurves of Type IIn supernovae (SNe IIn) are consistent with the predictions of wind breakouts [45–47] with inferred mass loss rates $\dot{M} > 10^{-3}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ [48– 53]. Suggested by some literature [54–61], the month-scale pre-SN "precursors" in SNe IIn before the explosions are common, providing an independent evidence for the existences of intense mass loss episodes in most SNe IIn preceding the explosion. Besides, for superluminous SNe (SLSNe), type II or type I, may originate from the interactions between the SN ejecta and the extended CSM [62–74]. Finally, the rapid follow-up observations suggests that SN 2013fs, a Type IIp SN (SN IIp), went through a mass-loss of the progenitor prior to the explosion at a high rate of $\sim 3\times10^{-3}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ [75]. What's more, the further early observations for dozens of rising optical lightcurves of Type II SNe candidates indicate that the SN 2013fs is not a special case and the mass loss episodes should be ubiquitous for regular Type II SNe [76].

The dense CSM would be formed due to continuous mass loss before the SN explosion. After the explosion, the shock waves generated by the interaction of the SN ejecta with the CSM could accelerate protons beyond PeV energies, and subsequently the inelastic *pp* collision between the accelerated protons and the shocked CSM can give rise to interesting multi-messenger signatures, such as high-energy gamma-ray emissions, neutrino productions, as well as X-ray, optical and radio emissions [77–82]. Such high-energy gamma-rays could reach a energy of $\sim$ 100 TeV, locating the sensitive energy range of LHAASO.

B. The multi-messenger signatures of the regular Type II SN ejecta-CSM interaction

For regular Type II SNe, productions of gamma-rays and neutrinos for the typical interaction of the SN ejecta and the SN 2013fs-like CSM is presented in Fig. 2, as in Ref. [82]. Due to the absorption of low-energy photon field in the emission region, the spectrum gets a significant suppression at the energy range of $\sim$ 10 GeV–100 TeV. Besides, the gamma-ray flux above tens of TeV will be reduced during the propagation to Earth as well, due to the absorption by the EBL and CMB photons. In Fig. 2, the sensitivities of *Fermi*-LAT, Cherenkov Telescopes Array (CTA) and LHAASO are shown to compare with the gamma-ray emissions. As we can see, for typical values of parameters, at 10 Mpc, high-energy gamma-rays are hard to be observed by all the three experiments for the case with the 2013fs-like CSM. However, for a time window of $\sim 10^{5.5}$s, at a distance $\lesssim 2-3$ Mpc, gamma-rays could be detected around GeV by *Fermi*-LAT, around few−100 TeV by the CTA and above $\sim$ 100 TeV by LHAASO. For a denser CSM environment (e.g., the red short dashed line in Fig. 2), the flux of gamma-rays is significantly enhanced and it could be still detectable for a further distance of source. The cooperative observations to gamma-rays from a ejecta-CSM interaction by the experiments in the future could be expected and a broad spectrum of gamma-rays from GeV to hundreds of TeV may be approached. Especially, LHAASO, which has a competitive sensitivity around 100 TeV, can provide the unique information of very-high-energy gamma-rays and can help us to expose the origin of cosmic rays more directly.

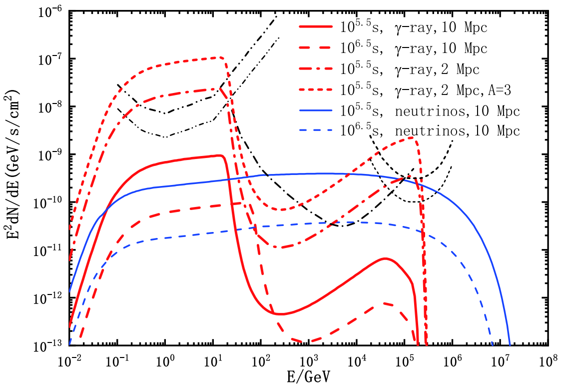

Fig. 2. (color online) The fluxes of produced gamma-rays (red thick lines) and neutrinos (blue thin lines) for a typical interaction of the SN ejecta with the CSM. The red solid, red dashed and red dash-dotted lines are shown for two different time windows, i.e., $10^{5.5}$s and $10^{6.5}$s and two representative source distances i.e., 2 Mpc and 10 Mpc by assuming that the CSM is SN 2013fs-like. Besides, the red short dashed line for the $A=3$ times denser CSM environment is presented as well. The black thick and thin dot-dot-dashed lines represent respectively the differential sensitivity of *Fermi*-LAT for a observational time $10^{5.5}$s and $10^{6.5}$s, the black dot-dashed line indicates the 50hr differential sensitivity of CTA, and the black short dashed lines indicate the differential sensitivity of LHAASO for a observational time $10^{5.5}$s and $10^{6.5}$s. For more details, please see [82].

In contrast to gamma-rays, which may be absorbed via photon-photon attenuation in the shocked region and during their propagation in the universe, neutrinos are more effective information carriers as they can escape from the source and propagate to Earth unimpeded. For the scenario with the SN CSM breakout as the point source of neutrinos, at $10\,\mathrm{Mpc}$, the flux is $\sim 3\times10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ (see Fig. 2), which could reach the sensitive level of future IceCube Gen2 [83]. If the source is located at a closer distance or with the Galaxy, those neutrinos could be detected by the current IceCube observatory [84]. The joint observations of high-energy gamma-rays by LHAASO and neutrinos by IceCube could become a reality in the future and then help us to determine the nature of these explosive phenomena, e.g., properties of the progenitor and the acceleration mechanism of cosmic rays [85]. For the high-energy gamma-rays, LHAASO is able to detect signatures of CSM breakouts of regular Type II SNe at $\lesssim 2-3\,\mathrm{Mpc}$ for a time window of several days. Such a size is comparable with the size of a local galaxy cluster. The expected regular Type II SN event rate in local galaxy cluster is about a few in ten years [86].

C. The multi-messenger detection probability of other types of CCSN

The SNe IIn may have a denser and more extended CSM than that of SNe IIp, resulting in a larger detectable distance of $\sim 10\,\mathrm{Mpc}$ and longer time window of month-scale for high-energy gamma-rays [78]. However, SNe IIn is relatively rare with a event rate of $7-9\%$ of all CCSNe [87, 88], and therefore the occurrence rate of nearby SNe IIn is $\sim 1\,\mathrm{yr}^{-1}$ within 30 Mpc and $\sim 0.03\,\mathrm{yr}^{-1}$ within 10 Mpc. In addition, during the propagation, the EBL attenuation is significant at $\gtrsim 100\,\mathrm{TeV}$ for a distance of $\gtrsim 10\,\mathrm{Mpc}$. As a result, high-energy gamma-rays observed by LHAASO can be operated only within $\sim 10\,\mathrm{Mpc}$ and with a event rate of $\sim 0.03\,\mathrm{yr}^{-1}$. However, this event rate is conservative since the SN rate density within $10\,\mathrm{Mpc}$ is higher than the global one [89] and more importantly, due to the detectable distance of high-energy neutrinos from SNe IIn up to $\sim 10\,\mathrm{Mpc}$ [78, 80], SNe IIn could be promising sources for multi-messenger observations. For Type Ibc SNe, whose rate is $\sim 20\%$ of CCSNe [87, 90], it may be difficult to implement such a joint multi-messenger owing to the lower expected flux, but it could be also possible if the CSM is as dense as that for low-luminosity gamma-ray bursts [91] or it takes place in a closer distance.

D. Summary

In summary, LHAASO can play an important role to participate in these multi-messenger observations for the CCSN ejecta-CSM interaction specifically by focusing on the very-high-energy gamma-ray observations. As the above estimation, LHAASO is able to detect high-energy gamma-rays of CSM breakouts for regular Type II SNe at $\lesssim 2-3\,\mathrm{Mpc}$ with a event rate around a few in ten years, and for SNe IIn at $\lesssim 10\,\mathrm{Mpc}$ with a event rate of $\sim 0.03\,\mathrm{yr}^{-1}$.

IV. EXTENDED/DIFFUSE SOURCES OF HIGH-ENERGY NEUTRINOS

The origins of astrophysical neutrinos could be either galactic or extra-galactic. The galactic origins include the TeV γ-ray point sources, the galactic center and the diffuse one in Fermi bubble region, galactic halo and galactic plane. According to the production site, two regions as galactic disk and halo are discussed in this section. The diffuse γ-rays observed by LHAASO in those regions can play very important roles to constrain the neutrino flux from the galactic contribution.

A. Contribution from the galactic plane

Besides various potential point-like neutrino sources, there are also possible extended neutrino sources. Galactic plane is actually a promising one because the hadronic interaction between cosmic rays and gas in ISM has been demonstrated by Fermi-LAT [92], ARGO-YBJ [93] and Tibet AS+MD array [16]. There has been analysis on the diffuse neutrino flux from the Galactic plane, and the upper limit is found to be $\sim 10\%$ [24, 94]. The diffuse gamma-ray emission from the Galactic plane at multi-TeV energy would be a direct indicator of Galactic high-energy neutrino flux, although the emission by unresolved faint gamma-ray sources may also contribute [95, 96]. Figure 3 shows the expected Galactic diffuse neut-

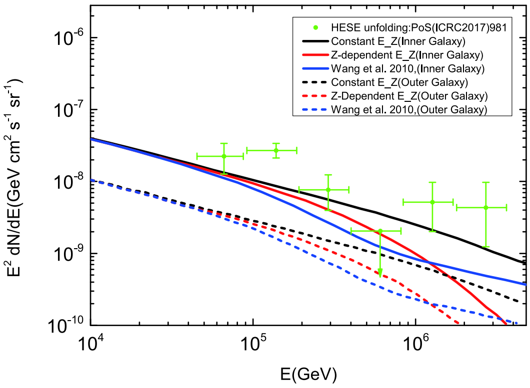

Fig. 3. (color online) Expected diffuse neutrino spectrum from the collision of the CRs with the ISM in the inner ($-30° < l < 30°$, $|b| < 5°$, upper solid) and outer ($90° < l < 270°$, $|b| < 5°$, lower dashed) Galactic plane regions, respectively. Also shown are the atmospheric muon neutrino background observed by IceCube and the recent IceCube results of possible astrophysical neutrinos.

rino spectrum under the conventional propagation model. These neutrinos originate from the collisions of the diffuse cosmic rays with the interstellar medium nearby the Galactic disk. The solid and dashed lines represent the contributions from the inner Galactic plane ($-30° < l < 30°$, $|b| < 5°$) and outer Galactic plane ($90° < l < 270°$, $|b| < 5°$) respectively. The Galactic diffuse neutrinos intensity is about $\sim 10\%$ of all-sky one, which is consistent with the IceCube's observation.

In addition, fresh cosmic rays injected recently from the sources could be detained by local magnetic fields. Recent observations revealed a universal hardening of γ-rays, e^+/e^- and B/C ratio from ~ 10 GeV, which indicate an additional hard component of cosmic rays and can be ascribed to these detained fresh cosmic rays. By interacting with local gases, these cosmic rays can generate additional gamma rays and neutrinos in the Galactic plane. Figure 4 shows the expected diffuse neutrino spectrum by the collisions between a hard galactic plane component and ISM. As can be seen, the theoretical calculation of all-sky flux including both conventional model and hard component is lower than the experimental observation, which contribute to $\sim 60\%$ of the IceCube observation [97]. Therefore the Galactic neutrinos could contribute between $\sim 10\%$ and $\sim 60\%$ of total neutrino flux observed by IceCube experiment. But as shown in the right panel of Fig. 4, the Galactic neutrino flux mainly comes from galactic plane by the black solid line. This significantly contradicts with the observations of the IceCube collaboration, which claimed an isotropic distribution based on the current number of neutrino events. It is possible that the extrapolation of the hard component to $\sim$ PeV is unlikely to be the right approach, which may overestimate the galactic contribution. The diffuse gamma-ray observations at ~ 100 TeV by the LHAASO experiment could constrain the Galactic neutrino contribution.

B. Contribution from Fermi-Bubbles and Galactic halo

In addition to the Galactic plane, the Fermi bubble could be another potential emitter of TeV-PeV gamma rays and neutrinos, via the *pp* collisions of protons or nuclei accelerated in or transported to the bubble region. Recently HAWC reported an absence of gamma-ray excess from the Northern bubble at $b \gtrsim 6°$ Galactic latitude, posing a flux upper limit in the energy range of $1.2-126$ TeV [98]. The upper limit is consistent with the gamma-ray spectrum measured by Fermi-LAT at $|b| \geq 10°$, where an exponential cutoff at energies $\gtrsim 100$ GeV is evident. However, the gamma-ray spectrum at $b \leq 10°$ does not show any cutoff feature up to around 1 TeV, and hence it remains a potential source for TeV-PeV gamma rays and neutrinos. It has been shown that LHAASO may constrain emission in the $0.1-100$ TeV range if $\leq 10\%$ systematic uncertainties can be achieved [99].

Furthermore, the extended halo of our Galaxy as a diffuse neutrino sources has also been studied by different groups [100–102]. It is suggested that Galactic cosmic rays that escape from the Galactic plane can interact with the diffuse hot gas in the halo, producing gamma rays and neutrinos. The large FOV of LHAASO is beneficial for the measurement of such a diffuse flux. After a long-term operation, either detection or nondetection of the diffuse sub-PeV photon from high Galactic latitude will be useful to evaluate neutrino flux originating from the extended halo. The high-latitude diffuse gamma-ray flux may also shed some light on the "missing" Galactic baryon content in the halo [102].

These result would also be important to understand the distribution and transport of sub-PeV/PeV cosmic rays in our Galaxy.

V. LHAASO PROBES THE ORIGIN OF ULTRA-HIGH ENERGY COSMIC RAYS

The origin of ultrahigh energy cosmic rays (UHECRs) is not solved yet. The sources of UHECRs may be also producing high energy gamma-rays and neutrinos via hadronic interactions. If the diffuse TeV-PeV neutrinos and UHECRs are produced in related processes, then LHAASO may be expected to identify TeV

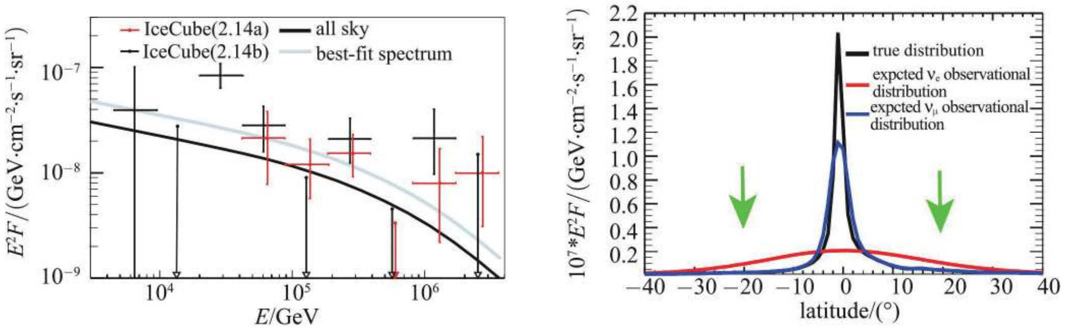

Fig. 4. (color online) The left panel shows the calculated diffuse neutrino spectrum from collision of CRs with ISM. The data is astrophysical neutrino observations. The right panel is the integrated neutrino flux for $E > 30$ TeV along $l = 0$. The black line is the true distribution in our model and the red is the reconstructed distribution for $\nu_e(\nu_\mu)$ after considering the angular resolution of $15°(1.5°)$.

gamma-ray sources from a fraction $\sim 0.1(n_s/10^{-5}\,\mathrm{Mpc}^{-3})^{-1/2}$ of the UHECR positions (with n_s being the source density). Even if the UHECR sources are too numerous and weak to detect, the non-detection can still put stringent constraint on the source density and hence the origin of UHECRs.

The origin of the observed UHECRs, $>10^{19.5}$ eV, is still unknown (see review [103]). Because of the Greisen-Zatsepin-Kuzmin (GZK) effect, the effective propagation length of cosmic rays with >50 EeV is only $d_{GZK}\lesssim 1$ Gpc. The UHECRs detected on the Earth should be originated from sources with a distance of $d<d_{GZK}$. Cosmic rays are deflected by magnetic field during propagation, but UHECRs of >50 EeV are expected to be deflected by only $<2^\circ$, assuming UHECRs are protons (see, e.g., [104]). Thus their arrival directions may trace back to the sources. Cosmic ray sources may also produce high energy gamma-rays and neutrinos by the hadronic interactions of cosmic rays. Using LHAASO to observe the positions of UHECRs may enhance the chance of finding the UHECR sources. Note, within 100 Mpc the gamma-gamma absorption due to the extra-galactic background lights may not be very important for TeV gamma rays. Therefore, high energy gamma-ray observations by LHAASO must be very helpufl to probe UHECR origin.

The IceCube-detected TeV-PeV neutrino flux is comparable to the Waxman-Bahcall bound, which is derived from observed UHECR flux. This may indicate that the origin of TeV-PeV neutrinos is related to the origin of UHECRs, i.e., the cosmic rays that result in the TeV-PeV neutrinos are with the same origin as the UHECRs [105]. If so, a TeV-PeV gamma-ray flux comparable to the TeV-PeV neutrino flux should also be accompanying the production of UHECRs. We here suggest LHAASO to search the high energy gamma ray signals from the UHECR positions.

Let us estimate the possible observational results by LHAASO. Derived from the IceCube detection, the gamma-ray emissivity, i.e., the energy production rate density in the universe, at ~ 10 TeV should be about $\dot\rho\sim 10^{43}\dot\rho_{43}\mathrm{erg\,Mpc^{-3}yr^{-1}}$ [106]. If the source density is $n_s=10^{-5}n_{-5}\,\mathrm{Mpc}^{-3}$, then the (average) gamma-ray luminosity of a single source is $L=\dot\rho/n_s$, and the maximum distance that the sources can be detected for a telescope of given sensitivity S is $d_M=(L/4\pi S)^{1/2}$. Since the integrated sensitivity of LHAASO at 3-TeV is $S_3\sim 6\times 10^{-14}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$ (for 1-yr exposure), the maximum distance is given by

$$d_M=54\dot\rho_{43}^{1/2}n_{-5}^{-1/2}(S_3/6\times10^{-14}\,\mathrm{TeV\,cm^{-2}\,s^{-1}})^{-1/2}\,\mathrm{Mpc}. \quad (3)$$

For comparison, the mean free path of 3-TeV gamma-rays in the intergalactic medium is larger, $d_\tau\sim 100$ Mpc. The number of sources that are within a distance of d_M is $N_s\approx\frac{4}{3}\pi d_M^3 n_s$, i.e.,

$$N_s\sim 6.6\dot\rho_{43}^{3/2}n_{-5}^{-1/2}(S_3/6\times10^{-14}\,\mathrm{TeV\,cm^{-2}\,s^{-1}})^{-3/2}. \quad (4)$$

As the exposure time increases, the sensitivity goes as $S\propto t^{-1/2}$, thus the number of observed sources for 10 yrs is

$$N_s\sim 40n_{-5}^{-1/2}(t/10\mathrm{yr})^{3/4}. \quad (5)$$

Here the source density has been normalized to a value typical for starburst galaxies, whereas the number of observed sources will decrease if the sources are more numerous, and hence weaker, $N_s\propto n_s^{-1/2}$.

These gamma-ray sources should lie in the directions of the observed UHECRs. For a certain UHECR experiment, the fraction of its detected UHECRs that are originated within a distance d_M is about $f_s\sim d_M/d_{GZK}$ ($d_M<d_{GZK}$), i.e., $f_s\sim 0.1n_{-5}^{-1/2}(t/1\,\mathrm{yr})^{1/4}$ for UHECRs of >50 EeV, which does not vary much with exposure time, $\propto t^{1/4}$. LHAASO can search for these gamma-ray sources by carrying out observations at a few TeV at the positions of the UHECRs that are detected by the Telescope Array (TA) experiment and Pierre Auger Observatory (PAO). A fraction f_s of these UHECR positions are expected to be identified with TeV gamma-ray sources. If the sources are too weak (i.e., n_s is large) to detect, we can carry out stacking analysis of all the TA and/or PAO detected UHECR positions. Due to the wide field of view and high sensitivity of LHAASO, even non-detection of signals will put stringent limit on the source density and hence the origin of UHECRs.

VI. SEARCH FOR NEUTRINOS WITH HORIZONTAL AIR SHOWERS FROM LHAASO

The observation of PeV cosmic neutrinos is an essential tool for understanding cosmic ray acceleration, composition and source evolution. These particles are produced either within astrophysical sources or when ultra-high energy cosmic rays interact in transit through the cosmic background radiation. Neutrino signals may accompany electromagnetic and gravitational messengers, or they may be the primary signal at the site of cosmic ray acceleration. Neutrino messengers from transient or flaring sources (AGN, GRB) are a topic of intense study. In 2018, the possible detection of a neutrino event by IceCube coincident with a gamma-ray flaring blazar opened the multi-messenger era [38]. The detection of cosmic neutrinos above energies of 10^{16} eV (= 10 PeV) has not yet been achieved.

A. Introduction

The observation of neutrinos through the detection of

Horizontal Air Showers (HAS) with the LHAASO experiment is the subject of this paper. In fact, the only way for an air shower array to observe such events is to look for HAS, i.e., showers with zenith angles >70° [107, 108]. The study of HAS is an important tool for UHE cosmic neutrinos measurement, in particular for the quest for prompt ν_e produced in GRBs [108].

The cosmic ray (CR) flux is a steeply falling function of zenith angle because the depth of atmosphere traversed by a shower reaching the ground rises rapidly from 1030 to about 36000 g/cm^2 as the zenith angle varies from zero to 90°. Thus near the horizon the interaction point is separated by about 1000 radiation lengths of matter from the detector. Most secondaries such as electrons, pions and kaons are absorbed in the dump and only penetrating particles, such as muons and neutrinos produced in the initial interaction, are able to reach the detector. Therefore, to CRs incident near the horizon the Earth's atmosphere represents a beam dump.

The observation of extensive air showers (EAS) in nearly horizontal directions provides a *"well shielded laboratory"* for the detection of penetrating particles: high energy muons, cosmic neutrinos, possible weakly interacting particles produced in the decays of cosmological superheavy particles, will leave a clear signature in this dump.

Measurements of the CRs rate at different zenith angles give information on the relative number of muons in a shower, which is dependent on the CR elemental composition, thus providing an important tool to probe the CR mass distribution [109]. In addition, for very high energy interactions the decay of charm particles is the dominant source of high energy secondary muons. So counting high energy muons at large zenith angles determines the charm cross section [110–112]. There is no background from the semi-leptonic decay of pions and kaons which, as a result of time dilation, interact and lose energy rather than decay into high energy muons.

The detection of EAS at large atmospheric zenith angles (Horizontal Air Showers, HAS) has been firstly reported in 1965 at an energy above 10^{14} eV [113]. In the seventies their origin has been studied by Bohm and Nagano [114], but their interpretation was not straightforward, due to the contradiction between the expected and detected muon contents. The EAS-TOP experiment studied in detail the phenomenology of HAS, finding that they are mainly due to muon-dominated showers produced by Ultra High Energy (UHE) cosmic rays interacting at very large distance in the atmosphere [115]. In the last years a big effort has been made to study in detail the phenomenology of these events with accurate MC simulations (see, e.g., [116–119]).

HAS are believed to be mainly due to the atmospheric muons and their interactions, as example:

(a) High energy single muons can interact through bremsstrahlung or deep inelastic scattering and initiate showers at the depth appropriate for detection. Such showers are essentially electromagnetic, since the remnant muons from the initial shower (whose typical primary energy is not much larger than the muon one) are dispersed over a very large area.

(b) UHE CRs interacting at the top of the atmosphere, at very large zenith angles, produce a "large" amount of muons through the pion decays (favoured, at large angles, with respect to pion interactions due to the low atmospheric density at the interaction altitude). Such showers are therefore composed essentially of muons since the e.m. component is completely absorbed.

Neutrino induced showers have some intermediate typology, being more similar to conventional CR air showers or to events (a), when a large amount of their energy is transferred to the electromagnetic cascade. EAS arrays must have the possibility of discriminating between the different typologies of events through μ/e identification. The LHAASO experiment, with an array of about 40,000 m^2 muon detector, is the most suitable apparatus for such studies.

B. Neutrino induced air showers in atmosphere

The weak interaction channels of neutrinos have been shown by literature [120]. In all cases about 20% of the energy of the primary neutrino is transferred to the hadronic jet which results from the nucleon debris. These particles initiate cascades very similar to those produced by protons. The remaining 80% of the primary particle's energy is contained in an ultra-energetic lepton. The actual energy transferred to the shower depends on the interaction channel and neutrino flavour.

If the shower is initiated by a ν_e through charged current (CC), the resulting electron initiates an electromagnetic shower overlapping the hadronic one produced by the jet. In this case, 100% of the energy is transferred to the shower. On the contrary, neutral current interactions (NC) produce a secondary neutrino instead of an electron. This neutrino escapes and does not contribute to the process of multiplication, carrying about 20% of the energy of the primary neutrino.

Inclined showers initiated by a ν_μ through CC are very similar to the ones initiated via NC.

The ν_τ via CC presents an interesting characteristic. In the same way as the muon, the τ lepton is a very penetrating particle which can travel an important distance from the point at which it was produced. On the other hand, its lifetime is seven orders of magnitude lower so it can decay before reaching the surface producing a secondary shower that is added to the one initiated by the hadronic jet. This kind of showers are commonly known as *"Double Bang"* (DB). Depending on the decay channel of the τ, the second shower will be of hadronic or electromagnetic nature.

The mean free path for neutrinos is much higher than the atmospheric depth. Neutrinos can interact at any point in the atmosphere with almost the same probability. In particular, neutrinos can initiate an inclined shower deep in the atmosphere, inside a fiducial volume in which the electromagnetic component reaches the surface. This characteristic distinguishes neutrinos from other possible particles like protons, nuclei or photons which interact in the first hundred grams of the atmosphere with a probability close to 1.

Tau neutrinos are not produced in the decay of charged pions, therefore they are suppressed in the neutrino production relative to ν_e and ν_μ. Nevertheless, after travelling cosmological distances, because of neutrino flavour mixing, the usual 1:2 of ν_e to ν_μ ratio at production is altered to approximately equal fluxes for all flavours [121].

A VHE ν_τ entering in the Earth or mountain can undergo charged-current interactions producing a tau lepton τ that can emerge into the atmosphere and decay in flight producing a nearly horizontal extensive shower [122]. Subsequently, it decays and produces an air shower. Particles or Cherenkov photons from the air shower are detected. Due to the separation of the first interaction where ν_τ produces tau and τ decay generating air shower, air shower observation becomes possible while preserving the huge target mass required to compensate for the low cross section of the first interaction. For this detection method, it is crucial for the τ to go through the Earth and/or mountain before its decay, and to develop the air-showers in the atmosphere in front of the detector after its decay. The Earth crust, with a density 1000 times greater than the air density ($\rho_{\rm Earth}$ = 2.65 g/cm^2), is a target much more massive than the atmosphere. Under a spherical Earth approximation the distance the neutrino has to go through is about 220 km at 89°. This means that 30% of these neutrinos should interact at this zenith angle. However, one needs also to consider the probability of the resulting τ escaping the Earth and decaying in a fiducial volume to be detected.

The tau decay probability depends on the tau energy E_τ. For reference, the tau decay length, with the γ-factor $\gamma = E_\tau/(m_\tau c^2)$, is $\gamma c\tau$ = 5 km$\times E_\tau/10^8$ GeV.

The Earth-skimming process (neutrino interaction in the Earth crust) only applies to tau neutrinos. The detection of electron neutrinos when interacting in the Earth is very suppressed as the resulting high energy electron will give rise to a shower in the Earth. The problem with muon neutrinos is that muons have a lifetime 7.5×10^6 longer than taus so even if they can escape the Earth they decay very high in the atmosphere and the particles from this up-going shower never reach the ground.

C. Search for 100 TeV ν_e from high-energy transients

High-energy transients, including gamma-ray bursts (GRBs), supernovae, and blazars, are potential sources of high-energy cosmic rays. Neutrinos are penetrating neutral particles, and among the four traditional messengers (charged cosmic rays, photons, gravitational waves and neutrinos), they maybe the best probe of the origin of cosmic rays.

The expected neutrino flux can vary by order of magnitude between GRBs due to the fluctuations in the burst parameters and several GRBs in the LHAASO data set will be not in the IceCube list. Moreover, core-collapse supernovae (SNe), which are believed to be the origin of long-duration (>2 s) GRBs, could produce neutrino bursts in events in which mildly relativistic jets interact inside the stellar envelope. The neutrino spectrum produced in these events (as, for instance, the "choked GRBs") is expected softer but very high in fluence.

This technique could represent a complementary methodology to search with large area arrays for ν_e associated to buried GRB jets which are predicted to generate a soft neutrino spectrum with a fluence at TeV energies a few orders of magnitude greater than that characterizing the GRBs observed in gamma-rays.

The search relies on the directional and temporal information coming from satellite observations. In the angular and time windows of the prompt emission we look at an excess of events with respect to the background air showers induced by high energy atmospheric muons which undergo catastrophic energy losses due to radiative processes. Electrons produced in the CC interaction can carry a significant fraction of the neutrino energy, about 50% at low energies, rising to 75% above 100 TeV. These electrons promptly initiate an electromagnetic cascade that can be detected if the neutrino interaction point is at the appropriate distance from the LHAASO array (inside a fiducial volume). Due to the limited longitudinal development of the shower, the target thickness is by far smaller than the one obtained by observing long-range high energy muons in IceCube or Cherenkov photons from tau showers.

Cascade events are also produced in CC interactions when the generated muon radiates knock-on electrons, bremsstrahlung photons or electron pairs, and in ν_τ CC interactions when the resulting tau decays into an electron (three body decay, about 18% branching ratio) or into mesons (about 64% branching ratio, but only 12% for two body decays). At any given neutrino energy all these showers have much less energy than that induced by the electrons generated in the ν_e interactions, and the contribution of these process can be at first neglected.

All the neutrino flavours can generate cascades via the NC interaction, producing hadronic jets. The contribution of these events is expected to be quite low, reflecting the combination of a smaller cross section (about a factor 3 at energies <100 TeV) and the decrease of the neutrino flux with the energy. Moreover, the energy deposited in the hadronic jet, less than 50% that of the neutrino, can be shared by more than one particle.

D. Observation of HAS with LHAASO

At zenith angles $\theta > 60°$ an excess of events is observed above the rate of EAS as expected from the exponential absoprtion (with $\Lambda_{\rm EAS} \approx 220$ g/cm^2) of the air shower electromagnetic component in the large atmospheric depth (see Fig. 5), which implies a decrease of the EAS counting rate with $\Lambda_c \approx 130$ g/cm^2.

The dependence of the barometric effect on the zenith angle, shown in Fig. 6, clearly shows a deviation from the secθ behaviour for sec$\theta > 2$. In fact, the barometric coefficient $\beta = \dfrac{1}{n}\dfrac{{\rm d}n}{{\rm d}x}$ (n = counting rate, x = atmospheric pressure) is related to zenith angle as: $\beta(\theta) = \beta(0°)\sec\theta$. This can be explained by the presence of a "non-attenuated" EAS component that dominates for angles larger than 70°. A particle (muon or neutrino) with $\theta > 70°$ interacting deep will present a young shower front.

The fair agreement with the expected spectral index makes us confident that the bulk of HAS observed by LHAASO are due to muon-induced showers.

E. Summary

The study of HAS has been long recognized as a useful tool to investigate the interactions of high energy muons and to detect ultra high energy neutrinos.

The LHAASO experiment, due to different detectors (water ponds, dense scintillator array, muon detectors and wide field of view Cherenkov telescopes) is well suited to measure HAS and observe neutrino-induced events in an unprecedented energy range, from TeV up to about 10^{16} eV. In particular, the unprecedented muon detection area (more than 40,000 m^2) will allow to discriminate neutrinos from the cosmic ray background in an excellent way.

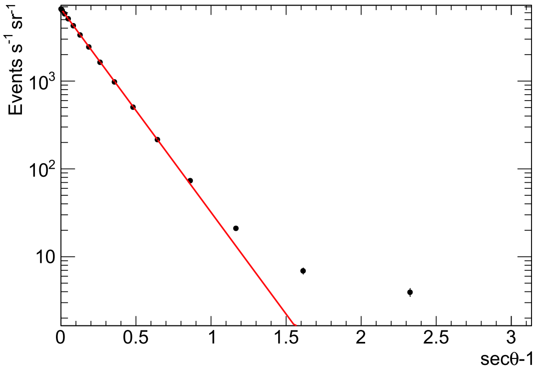

Fig. 5. (color online) The zenith angle distribution of EAS measured with LHAASO. The best fit out to ~60° is also shown.

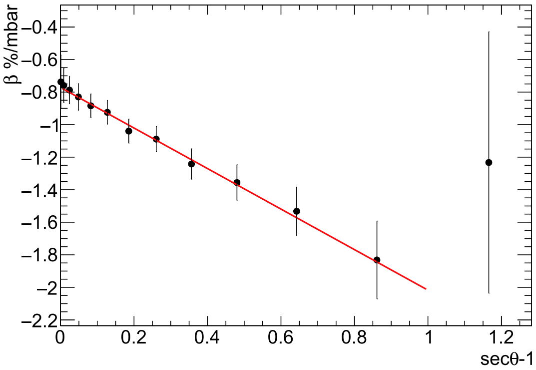

Fig. 6. (color online) The barometric coefficient for different zenith angles measured by LHAASO.

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