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Search for GeV neutrinos associated with solar flares with IceCube

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Solar flare neutrinos from the decay of mesons produced in collisions of accelerated ions from the solar atmosphere are expected with energies of O(MeV-GeV). The study of such neutrinos, combined with existing gamma-ray observations by the Fermi Large Area Telescope (LAT), would provide a novel window to the underlying physics of the acceleration process. The IceCube Neutrino Observatory may be sensitive to solar flare neutrinos and therefore provides a possibility to measure the signal or establish more stringent upper limits on the solar flare neutrino flux. A new approach dedicated to low energy neutrinos coming from transient events will be presented. It combines a time profile analysis and an optimized selection of solar flare events based on Fermi-LAT observations, significantly lowering the energy threshold of IceCube, which was initially designed to detect neutrinos with energies O(100 GeV) and above.

7th Fermi Symposium 2017
15-20 October 2017
Garmisch-Partenkirchen, Germany

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1. Introduction

In the late eighties, the Homestake experiment reported an increase in the total number of neutrino events that could be correlated with energetic solar flares [1]. According to the prediction of J.N. Bahcall, if this increase were indeed due to solar flares, it would lead to large characteristic signals in larger neutrino detectors [2]. In response, experiments such as Kamiokande [3] and SNO [4] performed several studies. Even though different solar flare samples and analyses were used, the experiments were not able to confirm the potential signal seen by Homestake.

Solar flares convert magnetic energy into thermal energy of plasma and kinetic energy of charged particles such as protons [5]. As a consequence of magnetic reconnection, protons are injected downwards from the coronal acceleration region and can interact with the dense plasma in the lower solar atmosphere. The consequent processes are indicated in Eq. 1.1 where the energy thresholds are 280 MeV and 180 MeV for p-p and p-α respectively.

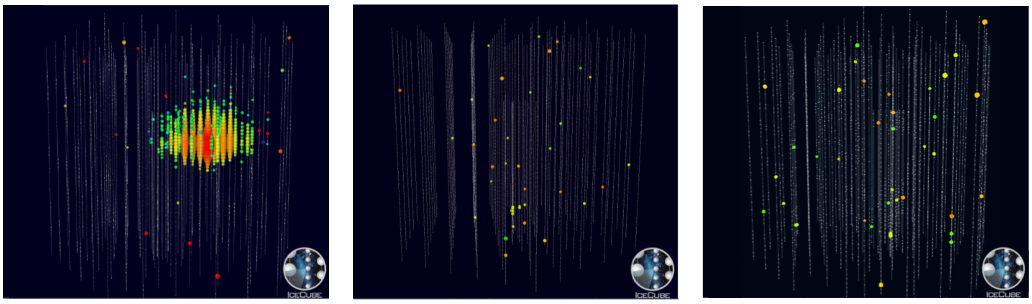
$$p + p \text{ or } p + \alpha \longrightarrow \begin{cases} \pi^+ + X;\ \pi^+ \longrightarrow \mu^+ + \nu_\mu;\ \mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \pi^0 + X;\ \pi^0 \longrightarrow 2\gamma \\ \pi^- + X;\ \pi^- \longrightarrow \mu^- + \bar{\nu}_\mu;\ \mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu \end{cases} \tag{1.1}$$

The main motivation to search for solar flare neutrinos comes from their hadronic origin. Being inherent products of high-energy proton collisions in the chromosphere, they represent a direct probe of the proton acceleration. Several studies (see e.g. [6, 7, 8]) have demonstrated that this neutrino flux could extend from MeV up to a few GeV. Neutrino facilities sensitive to this energy regime would therefore be able to open a new window on solar flare physics and provide new constraints on the proton spectral index. This work focuses on the IceCube Neutrino Observatory and its sensitivity to the high energy part of the neutrino spectrum from solar flares. Section 2 introduces a new event selection lowering the threshold of IceCube down to the GeV level. Combined with a dedicated time profile analysis described in Section 3, this selection allows IceCube to be sensitive to astrophysical transient events such as solar flares. Finally, Section 4 is dedicated to the potential reach of joint Fermi-LAT and IceCube observations of solar flares.

2. The IceCube Neutrino Observatory: from TeV to GeV

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole between depths of 1450 m and 2450 m [9, 10]. A lower energy infill, the DeepCore subarray, includes 8 densely instrumented strings with smaller spacing between its optical modules (7 m versus 17 m in the IceCube strings) and between its strings (72 m on average versus 125 m for non-DeepCore strings) [11]. When a neutrino interacts in the neighborhood of the detector, the subsequent electromagnetic and/or hadronic cascade emits Cherenkov photons that can be detected by one or more of the 5160 digital optical modules (DOMs) distributed over the 1 km^3 volume.

While IceCube was originally optimized to observe TeV and higher energy neutrinos, the collaboration has demonstrated the ability to extend the sensitivity to a larger energy range by the use of DeepCore. Since the observation of the first astrophysical neutrinos in 2013 [12], several noteworthy limits have been set on, among others, the existence of sterile neutrinos [13] and the



(a) PeV neutrino interaction (b) GeV neutrino interaction (c) Detector noise event

Figure 1: Examples of neutrino interactions as seen in IceCube. A typical GeV neutrino interaction is illustrated in 1b (simulation) while 1a (data) and 1c (simulation), respectively, show the well-known "Ernie" event in the PeV range and a noise event (see the text for more details).

spin-dependent WIMP-nucleon cross section [14] as well as competitive measurements of neutrino oscillation parameters [15]. The collaboration has also joined the worldwide multimessenger effort studying the highest-energy events in our Universe [16, 17]. We present a new approach extending the sensitivity down to energies around 1 GeV. Using external observations to define a time window of interest allows IceCube to study astrophysical transient events down to GeV scales.

Selection of GeV events

As previously mentioned, a subarray of IceCube, DeepCore, allows for search of low energy neutrino interactions. Besides a higher density of optical modules, a softer trigger condition has been implemented in DeepCore in view of increasing the sensitivity to lower neutrino energies. This softer trigger requires three hit optical modules satisfying a Hard Local Coincidence (HLC) [1] within a 2.5 μs time window. We also take advantage of the several running filters developed to tag specific physics events such as high-energy muons, cascades and very high-energy events [10]. A GeV interaction shows a very different signature from what is expected from these high-energy events as illustrated in Fig. 1. The low-energy event thus does not fulfill the conditions to pass the above filters. This failure to pass the filter offers a powerful tool to extract low energy interactions while removing high-energy neutrinos from the sample. This results in a significant reduction in the number of atmospheric muons – from the original rate of 1400 Hz to 15 Hz – while retaining more than 98% of signal events assuming a E^{-2} spectrum.

As one can see in Fig.1, the main difference between TeV and GeV neutrino interactions is the amount of light emitted in the ice. This leads to a very different number of optical modules able to detect the event. Putting strong upper constraints on the number of optical modules hit therefore eliminates neutrinos and remaining muons with an energy exceeding 5 GeV. An upper limit on the number of causally connected optical modules, i.e. the DOMs that have likely observed the same physics interaction, further helps to select low energy events. A GeV neutrino interaction indeed produces a small cascade or a short track emitting light close to the interaction vertex, resulting in a small number of causally connected DOMs while a high-energy event is expected to be seen by many DOMs.

[1] At least two hit DOMs in a nearest or next to nearest neighbor vertical span in a time window of $\pm 1 \mu s$.

The main obstacle in identifying GeV neutrino interactions in IceCube is the noise contamination due to detector effects. The random hits could trigger the detector by mimicking the pattern expected from a low-energy neutrino. A detailed simulation of noise in the detector helps to estimate the potential contamination of accidental triggers, hereafter referred to as "noise events". These include uncorrelated thermal noise, uncorrelated radioactive noise, and correlated scintillation noise [18]. About 6 Hz of pure noise survives the selection described above, and is at this stage the dominant contribution to the event sample. The way to minimize this contribution is to use causality between pairs of hits. This causality between two hits is satisfied if their effective speed - i.e. the distance between the two hits divided by the time separation between them - is consistent with the speed of light in ice. In practice, an event is classified as "physics" if it contains, during a W time window, a minimum of X pairs of hits with an effective speed falling in a [Y,Z] interval. A combination of different sets of values of [W, X, Y, Z] is used to optimize the selection of direct hits (signal) and the rejection of widely scattered hits (similar to noise). Applying this combination significantly reduces the rate of detector noise events, from 15 Hz to 0.2 Hz.

Additional variables describing the morphology of the events help to create a cleaner GeV neutrino sample. Among these variables, the depth and the charge located around the hit centroid as well as the total charge of the event allows reducing the data rate down to 0.02 Hz. More than 40% of the neutrino interactions below 5 GeV generated with *Genie* [19] with a generic E^{-2} spectrum pass this selection and are considered in the analysis as GeV event candidates. Even if this rate is slightly larger than the expectation of atmospheric neutrinos, estimated to occur at the mHz level, the selection is sensitive both to single transient events and for an event-stacking analysis.

3. Solar flare neutrinos

3.1 A specific solar flare selection

In order to increase the sensitivity of IceCube to solar flare neutrinos, we have developed a specific selection of solar flares. We focus on solar flares with high probability of pion production in order to optimize the search for neutrinos [20]. Due to their common production channel through the decay of pions, gamma-rays and neutrinos are expected to be emitted simultaneously. Using Fermi-LAT observations [21] therefore allows us to select solar flare events of interest as well as precise time windows for an optimal neutrino search.

Fermi-LAT has detected an impulsive phase in some of the latest solar flare events. Characterized by a small duration, these impulsive phases enable narrowing the neutrino search window to a few minutes. Moreover, analysis of the gamma rays detected during these short phases reveals a relatively hard initial proton spectrum, with a spectral index around 3, as well as an enhanced gamma ray yield [22]. In comparison, the long duration emissions manifest a softer proton spectral index (between 4 and 6) and a spread of the gamma-ray emission over several hours. Focusing on the impulsive phase of bright events therefore increases the chance of a neutrino detection in coincidence with solar flares.

3.2 The SFNews alert system

In order to increase even more the IceCube sensitivity to solar flare neutrinos, we have collaborated with Fermi-LAT scientists to create an alert system called *SFNews*. Based on the selection described above, the system is continuously searching for significant solar flare events in Fermi-LAT data in order to trigger IceCube. This alert system allows us to save IceCube data in a specific stream, called *HitSpooling*. HitSpool data, already used for supernova candidates, contains sub-threshold neutrino interactions happening in the neighborhood of IceCube in addition to the interactions triggering the detector. A dedicated analysis is ongoing and targets the very bright solar flares from September 2017.

4. Fermi-LAT and IceCube: the potential physics reach

Using the proton spectral index extracted from gamma-ray observations by Fermi-LAT [22] for each flare satisfying the selection described above, one can evaluate the average neutrino yield per proton. Additionally, a potential upper cutoff of the proton spectrum has been discussed in several studies (see e.g. [23]). The proton flux can therefore be defined as $\frac{d\phi}{dE} = AE^{-\delta}H(E_{max} - E)$, where A is a normalisation constant, δ represents the spectral index and E_{max} is the upper cutoff in a Heaviside function. The effect of this upper cutoff on the subsequent neutrino flux is illustrated in Fig. 2, where the blue (orange) points show the average neutrino yield per injected proton with δ = 3.2 and E_{max} =7 GeV (3 GeV). As can be seen on Fig. 2, an increase in the upper cutoff builds up the neutrino yield at lower energies. This comes from a wide spread in the energy loss distribution of the proton, or its daughter particle, before the neutrino production. A higher cutoff value also increases the maximum energy of the produced neutrinos. These two effects lead to a higher neutrino yield in the energy range targeted by the IceCube event selection described in Section 2. Coupling Fermi-LAT and IceCube observations, we have the potential to constrain both this upper cutoff and the spectral index by fitting the gamma-ray and neutrino spectra simultaneously.

5. Summary

We have described a new event selection that allows the IceCube Neutrino Observatory to be sensitive to GeV neutrinos, and therefore perform low-energy searches for astrophysical transient events, such as solar flares. This sensitivity to low-energy neutrinos can be achieved by the use of electromagnetic observations to define time windows of interest. Furthermore, we have developed a solar flare selection that focuses on events showing pion production in the gamma-ray light curve, further increasing the sensitivity of the neutrino search. This has been made possible thanks to collaborating with Fermi-LAT scientists. This collaboration also led us to build an alert system to save full detector information happening during a bright solar flare. Finally, we showed that coupling gamma-ray and neutrino observations together will allow us to constrain proton acceleration in solar flares, in particular the proton spectrum. As of today, no single astrophysical source has hadron acceleration detected with neutrinos. While gamma-ray observations have highlighted such acceleration process in several sources, neutrinos would constitute a smoking gun. Detecting solar flare neutrinos would provide unambiguous confirmation of hadron acceleration. This first detection would turn the Sun into a laboratory to understand hadron acceleration in general and joint interpretation of gamma/neutrino observations in other astrophysical sources.

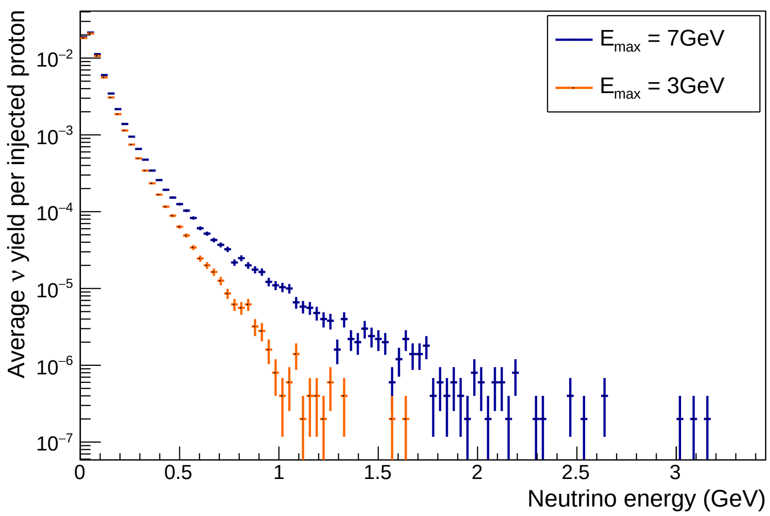


Figure 2: Average neutrino yield per injected proton with a spectral index of 3.2 and an upper cutoff of 7 GeV (blue) and 3 GeV (orange). A higher cutoff value leads to a higher neutrino yield in the energy range targeted by the event selection presented in this work.

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