

NEUTRINO ANALYSIS OF THE 2010 SEPTEMBER CRAB NEBULA FLARE AND TIME-INTEGRATED CONSTRAINTS ON NEUTRINO EMISSION FROM THE CRAB USING ICECUBE

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ABSTRACT

We present the results of a search for high-energy muon neutrinos with the IceCube detector in coincidence with the Crab Nebula flare reported on 2010 September by various experiments. Due to the unusual flaring state of the otherwise steady source we performed a prompt analysis of the 79-string configuration data to search for neutrinos that might be emitted along with the observed γ -rays. We performed two different and complementary data selections of neutrino events in the time window of 10 days around the flare. One event selection is optimized for discovery of E_ν^{-2} neutrino spectrum typical of first-order Fermi acceleration. A similar event selection has also been applied to the 40-string data to derive the time-integrated limits to the neutrino emission from the Crab. The other event selection was optimized for discovery of neutrino spectra with softer spectral index and TeV energy cutoffs as observed for various Galactic sources in γ -rays. The 90% confidence level (CL) best upper limits on the Crab flux during the 10 day flare are $4.73 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ for an E_ν^{-2} neutrino spectrum and $2.50 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ for a softer neutrino spectra of $E_\nu^{-2.7}$, as indicated by Fermi measurements during the flare. In this paper, we also illustrate the impact of the time-integrated limit on the Crab neutrino steady emission. The limit obtained using 375.5 days of the 40-string configuration is compared to existing models of neutrino production from the Crab and its impact on astrophysical parameters is discussed. The most optimistic predictions of some models are already rejected by the IceCube neutrino telescope with more than 90% CL.

Key words: gamma rays: general – ISM: supernova remnants – neutrinos – pulsars: individual (Crab Pulsar)

Online-only material: color figures

1. INTRODUCTION

This paper analyzes a specific flare of the Crab looking for neutrinos in time coincidence with it. Moreover, the impact of the steady emission limit of IceCube on neutrino production models from the Crab is described. Whether the emission is steady or time dependent, neutrinos can be produced in a source like the Crab if hadrons are accelerated in it and interact with matter or photons. We describe in what follows some of these models.

The Crab supernova remnant (SNR), originating from a stellar explosion at a distance of 2 kpc recorded in 1054 AD, consists of a central pulsar, a synchrotron nebula, and a surrounding cloud of expanding thermal ejecta (Hester 2008). Its bright and steady emission has made it a standard candle for telescope calibration. However, the photon emission stability in the X-ray and in the γ -ray regions has recently been questioned by a number of satellite experiments. As a matter of fact, a 7% decline of the Crab flux in the 3–100 keV region, larger at higher energies, has been observed in the period between 2008 and 2010 by the Fermi Gamma-ray Burst monitor and confirmed by *Swift*/Burst Alert Telescope (BAT), *Ross X-Ray Timing Explorer (RXTE)*/Proportional Counter Array (PCA), and *International Gamma-Ray Astrophysics Laboratory*

(*INTEGRAL*)/Imager on-Board *INTEGRAL* Satellite (IBIS) (Wilson-Hodge et al. 2011). The pulsed emission from *RXTE*/PCA observations is consistent with the observed pulsar spin-down suggesting that the decline is due to changes in the nebula and not in the pulsar.

The source of energy that powers the Crab is the spin-down luminosity of the pulsar. The measured spin-down luminosity of the pulsar is $\sim 5 \times 10^{38} \text{ erg s}^{-1}$ and its rotational period is 33 ms. While a small fraction of this energy goes into the pulsed emission, most of it is carried by a highly magnetized wind of relativistic plasma, the composition of which is not known. Both pure e^\pm plasma models and a mixture of e^\pm and protons or ions have been proposed (Hester 2008; Amato et al. 2003; Bednarek 2003; Bednarek & Protheroe 1997; Bednarek et al. 2005). The wind terminates in a standing shock and transfers some of the energy to accelerating particles. A part of this energy is converted into synchrotron emission from radio to MeV γ -rays by a population of high-energy electrons radiating in the nebular magnetic field. The observations of the synchrotron emission from the Crab up to the MeV energies make the Crab an undisputed Galactic accelerator able to inject electrons up to energies $\sim 10^{15} \text{ eV}$. These high-energy electrons inevitably interact with the ambient photon fields through inverse Compton scattering, resulting in the production of high-energy γ -rays observable in the TeV regime (Aharonian et al. 2000, 2006; Albert et al. 2008). The synchrotron emission from the Crab has an integrated luminosity of $\sim 1.3 \times 10^{38} \text{ erg s}^{-1}$, that is, at least $\sim 26\%$ of the spin-down luminosity of the pulsar is involved in the acceleration of electrons in the energy range 10^{11} – 10^{15} eV

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(Hester 2008). On the other hand, the presence of hadrons in the pulsar wind and the amount of energy transported by them remain as some of the unresolved and interesting questions about the Crab Nebula and plerions in general.

Protons and ions do not lose their energy as efficiently as electrons, and hence it is more difficult to observe the products of their interactions. The dominant processes, discussed below, are proton–proton and proton– γ interactions, and both processes generate γ -rays and neutrinos through meson decays. Hence, neutrinos constitute a unique signature for hadron acceleration while hadronic γ -ray production has to be disentangled from inverse Compton emission. Hadronic models of the Crab emission assume that the pulsar wind is composed of a mixture of electrons and ions. These models predict that a significant part of the rotational energy lost by the pulsar is transferred through the shock radius to relativistic nuclei in the pulsar wind. Relativistic nuclei injected into the nebula can interact with the nebula matter, and produce cosmic rays (CRs) and neutrinos via pion decay. Neutrino production by protons and nuclei interacting in the pulsar wind in the Crab has been discussed in Amato et al. (2003) and Bednarek (2003). According to these models, the nuclei can generate Alfvén waves just above the pulsar wind shock. These Alfvén waves will resonantly scatter off and accelerate the positrons and electrons that create the synchrotron emission. In the model described in Bednarek & Protheroe (1997) neutrinos are produced by heavy nuclei accelerated by the rotating neutron star that photodisintegrate in collisions with soft photons. These models predict between 1 and 5 events per year in a cubic-kilometer detector such as IceCube when accounting for neutrino oscillations. Inelastic nuclear collisions are considered in Amato et al. (2003). In this paper, the predicted rates depend on the Lorentz factor, Γ , of nuclei injected by the pulsar and the effective target density. The thermal matter distribution in the Crab is far from being uniform but forms filaments. For relativistic protons the effective target density is also affected by the structure of the magnetic field in and around these filaments. The authors in Amato et al. (2003) provide several expected neutrino fluxes from the Crab Nebula as a function of energy, for different assumptions on these two parameters. For the highest values of the effective target density, IceCube begins to have the sensitivity to probe the highest possible values around $\Gamma \lesssim 10^7$ while the favored values of the upstream Lorentz factor of the wind are $\Gamma \sim 10^6$ (Gallant & Arons 1994).

Acceleration of positive ions near the surface of a young rotating neutron star ($\lesssim 10^5$ yr) has also been investigated in Link & Burgio (2005). This model describes how positive ions can be accelerated to ~ 1 PeV in rapidly rotating pulsars, with typical magnetic fields ($B \sim 10^{12}$ G), by a potential drop across the magnetic field lines of the pulsar. Assuming that the star’s magnetic moment μ and the angular velocity Ω satisfy the relation $\vec{\mu} \cdot \vec{\Omega} < 0$, protons are accelerated away from the stellar surface. Beamed neutrinos (in coincidence with the radio beam) are produced by such high-energy protons interacting with the star’s radiation field when the Δ production threshold is surpassed. Observation of these neutrinos could validate the existence of a hadronic component and a strong magnetic field near the stellar surface that accelerates the charged particles. The predictions in Link & Burgio (2006) based on this model account for ~ 45 neutrino events per year from the Crab in a cubic-kilometer detector in the most optimistic scenario where the fraction of charge depletion is assumed to be $f_d \sim 1/2$. In this paper we will show that IceCube data severely constrain these optimistic predictions of the model.

In Kappes et al. (2007) a mean prediction of 1.2 neutrino events per year for $E_\nu > 1$ TeV was calculated for an underwater cubic-kilometer detector. This prediction is based on the H.E.S.S. measured γ -ray spectrum (Aharonian et al. 2006) assuming that all the γ -rays observed by H.E.S.S. up to 40 TeV are produced by pion decay and that the absorption of γ -rays is negligible. A similar calculation connecting photon and neutrino fluxes was done in Alvarez-Muniz & Halzen (2002), predicting about five events from the Crab accounting for neutrino oscillations. For a summary of some of the models on neutrino spectra the reader is referred to Bednarek et al. (2005).

From 2010 September 19 to 22 the *AGILE* satellite (Tavani et al. 2011) reported an enhanced γ -ray emission above 100 MeV from the Crab Nebula. The flare, however, was not detected in X-rays by *INTEGRAL* (Ferrigno et al. 2010) observations between September 12 and 19 partially overlapping with *AGILE* observations. It was also not confirmed by the *Swift*/BAT (Markward 2010) in the 15–150 keV range nor by *RXTE* (Shaposhnikov 2010) on a dedicated observation of the Crab on September 24. The observation was later confirmed by the Large Area Telescope on board the *Fermi Gamma-ray Space Telescope* that detected a flare of γ -rays ($E_\gamma > 100$ MeV) with a duration of ~ 4 days between September 19 and 22 in the Crab direction (Abdo et al. 2011a). The observed energy spectrum during the flare interval was consistent with a negative power law with a spectral index of -2.7 ± 0.2 . The flux increase was a factor 5.5 ± 0.8 above the average flux from the Crab. *Fermi* also detected another flare of 16 days in 2009 February corresponding to a flux increase of a factor 3.8 ± 0.5 but much softer spectral index (-4.3 ± 0.3). The ARGO-YBJ Collaboration also issued an ATel on 2010 September on the observation of an enhancement of the TeV emission for the same period of time but with a wider interval of 10 days. The enhanced TeV emission corresponded to a flux about 3–4 times higher than the usual Crab flux in TeV energies (Aielli et al. 2010). However, this observation was not confirmed by *MAGIC* (Mariotti et al. 2010) nor *VERITAS* (Ong et al. 2010); imaging Cerenkov telescopes in a similar energy range as ARGO-YBJ. The spectral and timing properties of the flares indicate that the γ -rays are emitted via synchrotron radiation from PeV electrons from a region smaller than 1.4×10^{-2} pc. This dimension is comparable to the jet knots observed close to the termination shock of the Crab Nebula (Tennant et al. 2010). Even though the Crab has always been considered to be a source of synchrotron emission, the flare represents a challenge to shock diffusive acceleration theory (Abdo et al. 2011a). Nonetheless, explanations of the high variability due to electromagnetic phenomena have been proposed in Bednarek & Idec (2011) where the emission comes from a part of the pulsar wind shock.⁴²

The unusual flaring state of this otherwise steady source, the intensity of the flare, and the experimental observations in γ -rays motivated this search for neutrinos in IceCube in coincidence with the Crab flare of 2010 September. In Section 5 we consider the steady neutrino emission from the Crab and how it compares to the time-integrated limit. Hadronic emission during flares like the 2010 September one has not yet been described by models. Nonetheless, the enhanced flux in photons could

⁴² During the final stage of the editing of this paper another large flare was observed from the Crab (Abdo et al. 2011b). This flare is even more intense than the one observed in September and is being studied by various experiments. Hence, IceCube analysis will happen when results from *Fermi*, other X-ray satellites, and other TeV ground-based experiments are available.

indicate that some of the parameters assumed in these neutrino models may be largely enhanced during flaring intervals, and in a not easily predictable way since experimental observations are based on the photon emission. Hence, it is valuable to look for neutrinos in coincidence with such flares with IceCube in a multi-messenger approach.

The IceCube Collaboration started a prompt analysis of the 2010 September data using the then-running 79-string configuration. The time window selected for this analysis was the interval of 10 days reported by ARGO-YBJ from September 17 to September 27, which contains the Fermi flare window. An unbinned maximum likelihood (log-likelihood; LLH) method described in Braun et al. (2010) has been applied to search for an excess of neutrinos in coincidence with the enhanced γ -ray emission from the Crab. The non-observation of neutrinos would reinforce pure electromagnetic emission scenarios and determine the level at which hadronic phenomena superimposed on an electromagnetic scenario can be probed.

The IceCube Neutrino Observatory is a neutrino telescope installed in the deep ice at the geographic South Pole. The final configuration comprises 5160 photomultipliers (PMTs; Abbasi et al. 2010) along 86 strings instrumented between 1.5 and 2.5 km in the ice. Its design is optimized for the detection of high-energy astrophysical neutrinos with energies above ~ 100 GeV. The observation of cosmic neutrinos will be a direct proof of hadronic particle acceleration and will reveal the origins of CRs and the possible connection to shock acceleration in SNRs, active galactic nuclei (AGNs), or gamma-ray bursts (GRBs). The IceCube detector uses the Antarctic ice as the detection volume where muon neutrino interactions produce muons that induce Cerenkov light. The light propagates through the transparent medium and can be collected by PMTs housed inside digital optical modules (DOMs). The DOMs are spherical, pressure resistant glass vessels each containing a 25 cm diameter Hamamatsu PMT and its associated electronics. Eight densely instrumented strings equipped with higher quantum efficiency DOMs form, together with 12 adjacent IceCube strings, the DeepCore array that increases the sensitivity for low-energy neutrinos down to about 10 GeV. Detector construction finished during the austral summer of 2010–2011.

This paper describes in Section 2 the data selection, the comparison to simulation, and the detector effective area and angular resolution for this search; in Section 3 we summarize the analysis method used; in Section 4 the results for the flare search are presented. Given the null result, upper limits are provided. In Section 5 the time-integrated upper limits based on one year of data of the 40-string configuration are presented to summarize what is the impact of the IceCube’s most sensitive limit on existing neutrino production models for the Crab. Conclusions are given in Section 6.

2. DATA SELECTION AND COMPARISON TO MONTE CARLO

The detection principle of IceCube is based on the charge and time measurement of the Cerenkov photons induced by relativistic charged particles passing through the ice sheet. The PMT signal is digitized with dedicated electronics included in the DOMs (Abbasi et al. 2009b). A DOM is triggered when the PMT voltage crosses a discriminator threshold set at a voltage corresponding to about 1/4 photoelectron. Various triggers are used in IceCube. The results shown here are based on a simple multiplicity trigger requiring that the sum of all triggered DOMs in a rolling time window of $5 \mu\text{s}$ is above

8 (SMT8). The duration of the trigger is the amount of time that this counter stays at or above 8 as the time window keeps moving. Once the trigger condition is met, all local coincidence hits are recorded in a readout window of $\pm 10 \mu\text{s}$ for the 40-string run and of ${}_{-4}^{+6} \mu\text{s}$ (to reduce the noise rate) in the 79-string run. IceCube triggers primarily on down-going muons at a rate of about 1.8 kHz in the 79-string configuration. Variation in the trigger rate determined by atmospheric muons is about $\pm 10\%$ due to seasonal changes (Tilav et al. 2010). Seasonal variations in atmospheric neutrino rates are expected to be a maximum of $\pm 4\%$ for neutrinos originating near the polar regions. Near the equator, atmospheric variations are much smaller and the variation in the number of events is expected to be less than $\pm 0.5\%$ (Ackermann & Bernardini 2005).

For searches of neutrino point sources in the northern sky, IceCube can use the Earth as a shield to reduce the background of atmospheric muons and detect up-going muons induced by neutrinos. In the northern sky these searches are sensitive to neutrinos in the TeV–PeV region.

In order to reconstruct muon tracks an LLH-based reconstruction is performed at the South Pole (L1 filter) providing a first-order background rejection of poorly reconstructed events and a selection of high-energy muons for the southern sky. The data sent through the satellite to the north undergo further processing that includes a broader range of more CPU-consuming reconstructions. This offline processing also provides useful variables for background rejection, measurements of the energy, and of the angular uncertainty, and selects about 35 Hz of the SMT8 data. However, the offline processing requires a fair amount of time to be finalized and is not suitable for expedited analysis. For the analysis of the Crab flare we used a dedicated selection for target of opportunity programs (Franckowiak et al. 2009; Ackermann et al. 2008). This online event selection and reconstruction is called the online Level 2 filter and selects about 4 Hz of data. It provides a reduced data rate (compared to the standard online data) because of stricter cuts than in the offline filter. The loss of sensitivity of this stream of data is marginal for E^{-2} neutrino spectra.

The online L2 filter performs an eight-fold iterative single photoelectron (SPE) LLH fit for events with the number of DOMs triggered fewer than 300 and a four-fold iterative SPE fit otherwise. These SPE fits are seeded by a track obtained using a single iteration LLH fit (Ahrens et al. 2004). While the online Level 2 selects good quality tracks and high-energy muons from the northern sky, it is dominated by the background of down-going atmospheric muons and therefore further cuts have to be applied before performing neutrino source searches. Experimental and simulated data are processed and filtered in the same way. The data used for this search concern the period from 2010 August 10 to 2010 October 12. In this period the detector was running in a stable configuration. The total live time for that period (considering dead times) is 60.9 days. Figure 1 shows the data rate of each run included during the selected time window as well as the South Pole atmospheric temperature. As can be seen at this level, the rate is dominated by down-going atmospheric muons, which display larger weather-dependent variations than the final up-going neutrino events.

We have performed two dedicated selections starting from the online L2 filter that we describe below.

2.1. Straight Cuts Data Selection

This data set is obtained by requiring a good level of reconstruction and ensuring degree level accuracy in the tracking

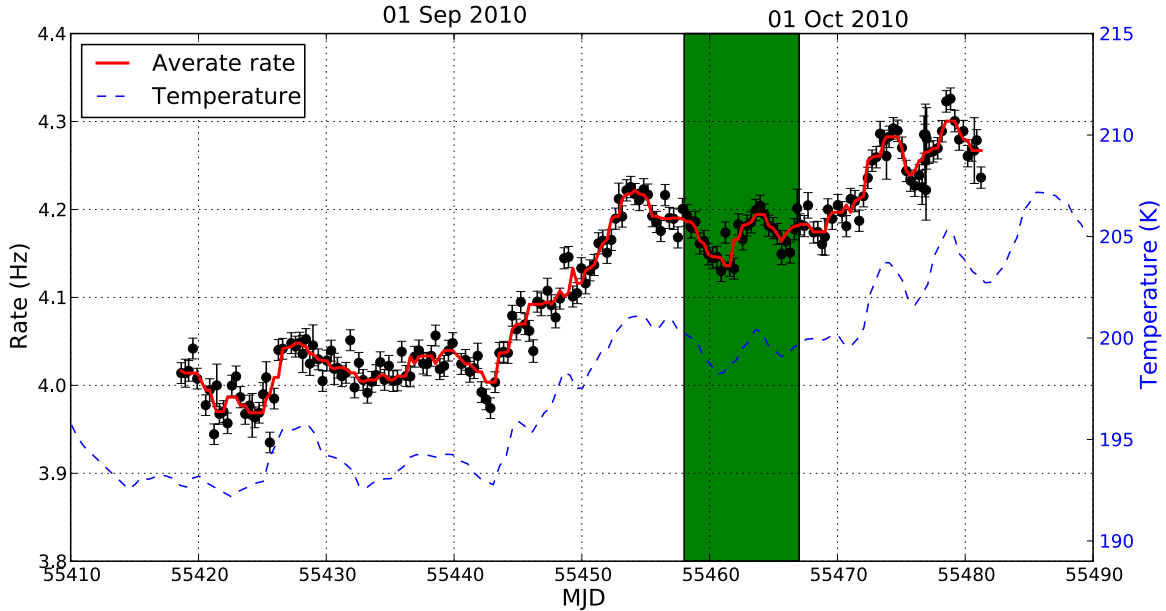


Figure 1. Data rates per run of the online Level 2 filter of 79 IceCube strings in the time window of the Crab flare. The green bar indicates the flaring interval used in this analysis according to ARGO measurements (Aielli et al. 2010). The blue dotted line indicates the temperature in the middle stratosphere of the South Pole according to Tilav et al. (2010).

(A color version of this figure is available in the online journal.)

errors to reject the misreconstructed down-going atmospheric muons from the real up-going atmospheric neutrino sample. The variables used are determined in the offline data processing and have been used for the 40-string point-source analyses in Abbasi et al. (2011a, 2011b). The final cut level can be achieved by applying the following series of cuts on a number of variables to obtain a good agreement between data and the simulation of atmospheric neutrinos, with a contamination of the order of 5% of atmospheric muons, mainly muons from two CR showers in coincidence in the same readout window. Having these muons with different directions gives hit patterns that confuse the reconstruction so that at times the result is a misreconstructed up-going track. The cuts are

$$\begin{aligned}
 N_{\text{dir}} &\geq 5; L_{\text{dir}} > 200 \text{ m}; \sigma_{\text{cr}} < 5^\circ; \\
 L_{\text{red}} &\leq \begin{cases} 7.4 & \text{if } L'_{\text{red}} \leq 6.4 \\ 8.0 & \text{otherwise,} \end{cases} \quad (1)
 \end{aligned}$$

where

1. N_{dir} is the number photons detected within -15 and 75 ns with respect to the expected arrival time of unscattered photons from the reconstructed muon track. Scattering of photons in the ice causes a loss of directional information and will delay them with respect to the unscattered expectation;
2. L_{dir} is the maximum distance in meters between direct photons projected along the best muon track solution;
3. σ_{cr} is the uncertainty on the reconstructed track direction given by the LLH-based track reconstruction estimated by a method based on the Cramér–Rao inequality (Cramér 1946; Rao 1945); and
4. L_{red} and L'_{red} are the standard reduced and modified LLH values, respectively. The reduced LLH is defined as the $-\log_{10}$ of the LLH value of the track reconstruction divided by the number of degrees of freedom. The number of degrees of freedom is the number of hit DOMs minus five fit parameters, two angles, and three coordinates of

Table 1
Data, Atmospheric Muon, and Neutrino Expected Background Rates for Different Cut Progression

Cut Level	Data Rate (Hz)	Atm. μ Rate (Hz)	Atm. ν_μ Rate (Hz)	E^{-2} Eff. (%)
Trigger	1800	1800	2.59×10^{-2}	...
Online Level 2	4.03	3.11	7.2×10^{-3}	100
Straight Cuts	4.6×10^{-4}	~ 0	4.8×10^{-4}	55
BDT	8.4×10^{-4}	~ 0	8.2×10^{-4}	61

Note. The signal efficiency for an E^{-2} neutrino spectrum assuming an emission $\pm 10^\circ$ around the Crab with respect to the online Level 2 is also shown.

a reference point along the track. It was found by comparing background rejection efficiency to signal selection efficiency that a good variable for rejection of background for low-energy events is the number of hit DOMs minus an effective number of degrees of freedom of 2.5.

An additional cut to select events in the direction of the Crab ($\Theta_{\text{Crab}} = 122^\circ$ at the South Pole) has also been applied: $\Theta_{\text{Crab}} - 10^\circ < \theta_{\text{rec}} < \Theta_{\text{Crab}} + 10^\circ$, where θ_{rec} is the reconstructed zenith angle of the muon track. No further selection in right ascension has been applied. In Table 1, the selected number of events and the expected number of atmospheric neutrinos and muons are given. The final number of events selected for the 10 day window of the flare is 354.

2.2. BDT Data Selection

The second data set is obtained by using a multi-variate learning machine. In particular this data selection is based on the knowledge and experience from previous analyses looking for solar weakly interactive massive particles (WIMPs) with the IceCube detector (Abbasi et al. 2009a). During the austral winter the Sun is below the horizon at the South Pole and its maximum declination is equal to the obliquity of the ecliptic, 23.4° . Since the Crab Nebula lies fairly close to the ecliptic

plane, the strategies and cuts that are optimized for this specific direction can be applied for the Crab direction.

Starting with the online L2 filtered data selection, as described above, a number of additional cuts were applied. The hereby selected events fulfill criteria of horizontal tracks passing the detector, to further minimize vertical tracks associated with background events. Additionally, the cuts were chosen to reduce the tails of distributions of the background into the signal region:

$$\begin{aligned} z_{\text{travel}} > -10 \text{ m}; \quad \sigma_{\text{COG}_z} < 170 \text{ m}; \quad \sigma_{\text{cr}} < 10^\circ; \\ \rho_{\text{av}} < 150 \text{ m}; \quad t_{\text{accu}} < 3000 \text{ ns}, \end{aligned} \quad (2)$$

where

1. z_{travel} measures the difference in the z positions of the center of gravity (COG) of the hits at the beginning of an event (first 1/4 of the hits in time) and the COG at the end of the event (last 3/4 of the hits in time);
2. σ_{COG_z} is the uncertainty in meters of the z -coordinate of the COG;
3. ρ_{ave} is the mean minimal distance between the LLH track and the hit DOMs; and
4. t_{accum} is the accumulation time, defined as the time until 75% of the total charge develops in ns.

Boosted decision trees (BDTs; Kerthi et al. 2001), multivariate learning machines, were used in the final analysis step to classify events as signal-like or background-like. Eleven event observables, split into two sets of five and six each, were obtained by choosing parameters with low correlation in background (correlation coefficient $|c| < 0.5$), but high discriminating power between signal and background. The selected observables include N_{dir} , L_{dir} , σ_{cr} , and L'_{red} as described within the straight cuts data selection in Section 2.1 and z_{travel} from above. Additionally, observables specifying the geometry, the time evolution of the hit pattern, the quality and consistency of the various track reconstructions that are defined through the opening angle between the line fit and the LLH tracks, and the number of hit strings are used. Training was done with simulated signal events for a soft neutrino spectrum of E^{-3} that also well represents the case of an E^{-2} spectrum with a TeV cutoff. A set of off-time real data, not used in the flare analysis, was used for training as background. The final sample is defined by a cut on the combined output (score) of the two BDTs. As in the case of the straight cuts sample, an additional requirement of reconstructed zenith tracks within $\pm 10^\circ$ from the Crab has been applied. In Table 1, the selected number of events and the expected number of atmospheric neutrinos and muons are given. The final number of events selected for the 10 day window of the flare is 660 events in the northern sky.

2.3. Comparison Data—Monte Carlo and Detector Performance

The simulation of atmospheric and signal neutrinos that is used for determining the selection efficiency, the performance of the detector and to calculate upper limits is based on the neutrino generator ANIS (All Neutrino Interaction Simulation; Gazizov & Kowalski 2005) and the deep inelastic neutrino–nucleon cross sections with CTEQ5 parton distribution functions (Lai et al. 2000). Neutrino simulation can be weighted for different fluxes, accounting for the probability of each event to occur. In this way, the same simulation sample can be used to represent atmospheric neutrino models such as Bartol (Barr et al. 2004) and Honda (Honda et al. 2007) neutrino fluxes from pion and kaon decays

(conventional flux) and a variety of models for the charm component (prompt flux; Martin et al. 2003; Enberg et al. 2008). Muons from CR air showers were simulated with CORSIKA (Heck et al. 1998) with the SIBYLL hadronic interaction models (Ahn et al. 2009). An October polar atmosphere, an average case over the year, is used for the CORSIKA simulation. Seasonal variations are therefore to be expected less than $\pm 10\%$ in event rates (Tilav et al. 2010). Muon propagation through the Earth and ice are done using Muon Monte Carlo (MC) (Chirkin & Rhode 2004). This simulation is used to verify the level of agreement of data and MC from trigger level to Level 1 and to understand the level of contamination at final cut level. For the optical properties of the ice we used a model obtained from calibrations using the light-emitting diodes in the DOMs called flashers (R. Abbasi et al., in preparation). This model produces a better agreement between data and MC than the model previously used (Ackermann et al. 2006). The simulation propagates the photon signal to each DOM using light tracking software described in Lundberg et al. (2007). The simulation of the DOMs includes their angular acceptance and electronics. The systematic errors on the simulation of the signal used to produce the upper limits have been evaluated and presented in Section 6 of Abbasi et al. (2011a) describing the 40-string time-integrated point-source search. The main uncertainties on the limits for an E^{-2} signal of muon neutrinos come from photon propagation, absolute DOM efficiency, and uncertainties in the Earth density profile and muon energy loss, accounting for a total of 16%.

Figure 2 shows the data and simulation comparison for some variables at the final cut level for the two data samples. As can be seen, the BDT sample increases the overall rate by allowing more low-quality reconstructed events (high L_{red}) than the straight cut sample. This is translated into a higher neutrino effective area at low energies but also a worse angular resolution as can be seen in Figure 3.

3. LIKELIHOOD ANALYSIS

The method used for this analysis is an unbinned likelihood method (Braun et al. 2010). This method looks for a localized statistically significant excess of neutrinos above the background in the direction of the Crab in coincidence with the flare. The same analysis technique has already been applied to AGN flare searches in IceCube (Abbasi et al. 2011b). The method uses both the reconstructed direction of the events as well as an energy proxy, the reconstructed visible muon energy, to discriminate any possible signal from background during the time interval of the flare. We consider the largest time window of 10 days reported by ARGO-YBJ. The applied method describes the data as a two-component mixture of signal and background. For a data set with N total events the probability density of the i th event is given by

$$\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i, \quad (3)$$

where \mathcal{S}_i is the density distribution for the signal hypothesis and \mathcal{B}_i for background. The parameter n_s is the number of signal events and one of the free parameters of the likelihood maximization together with the spectral index, γ , of the signal spectrum distribution. The likelihood of the data is the product of all event probability densities:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^N \left[\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right]. \quad (4)$$

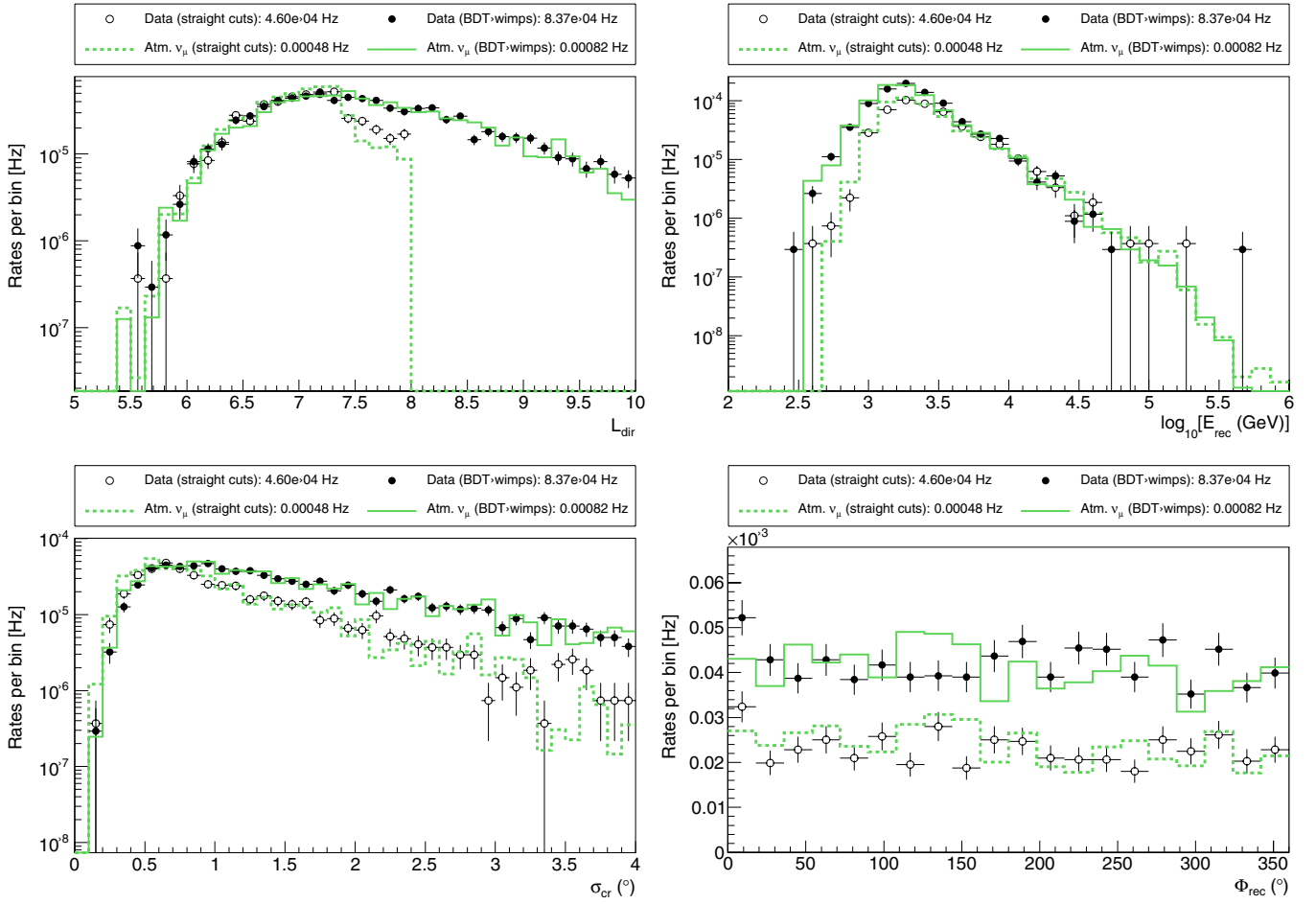


Figure 2. Top left plot shows the reduced log-likelihood (L_{red}), as defined in Section 2, distribution for both data (dots) and atmospheric neutrino simulation (green lines) for the two data samples. The distribution of the reconstructed energy is shown on the top right plot. The estimated angular error given by the track reconstruction algorithm using the Cramér–Rao upper bound is shown on the bottom left plot while the bottom right shows the azimuth distribution of the final data samples.

(A color version of this figure is available in the online journal.)

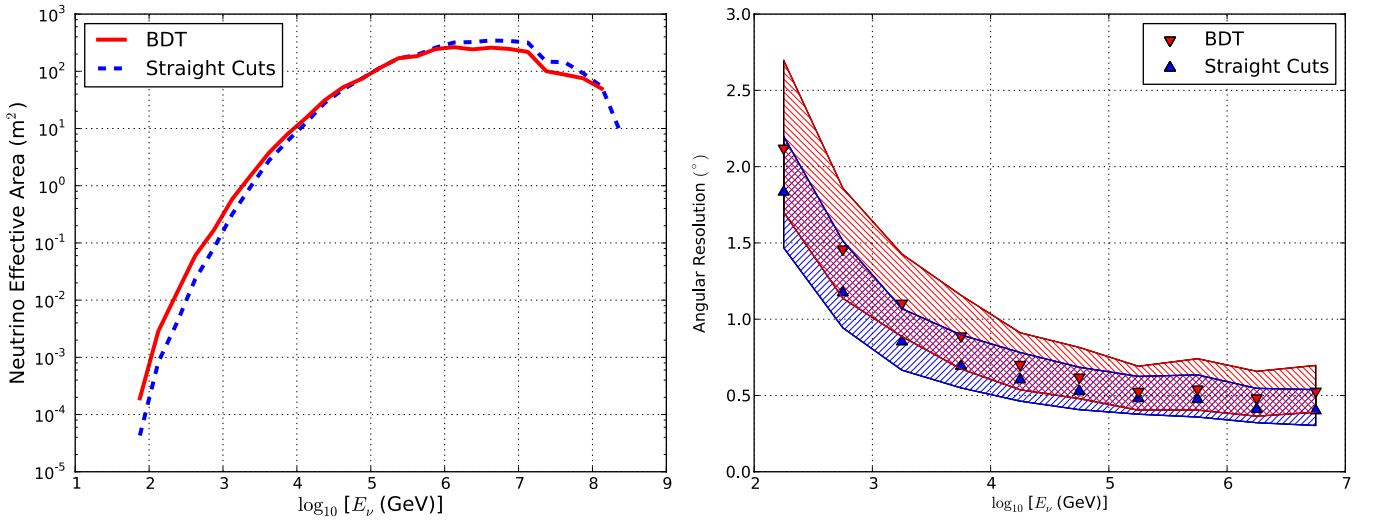


Figure 3. Left: muon neutrino effective area for the two final data samples in a zenith bin of $\pm 10^\circ$ from the direction of the Crab Nebula. Right: angular resolution defined as the median of the point-spread function as a function of the neutrino energy for the two data samples. The shaded areas represent a $\pm 10\%$ area of the point-spread function.

(A color version of this figure is available in the online journal.)

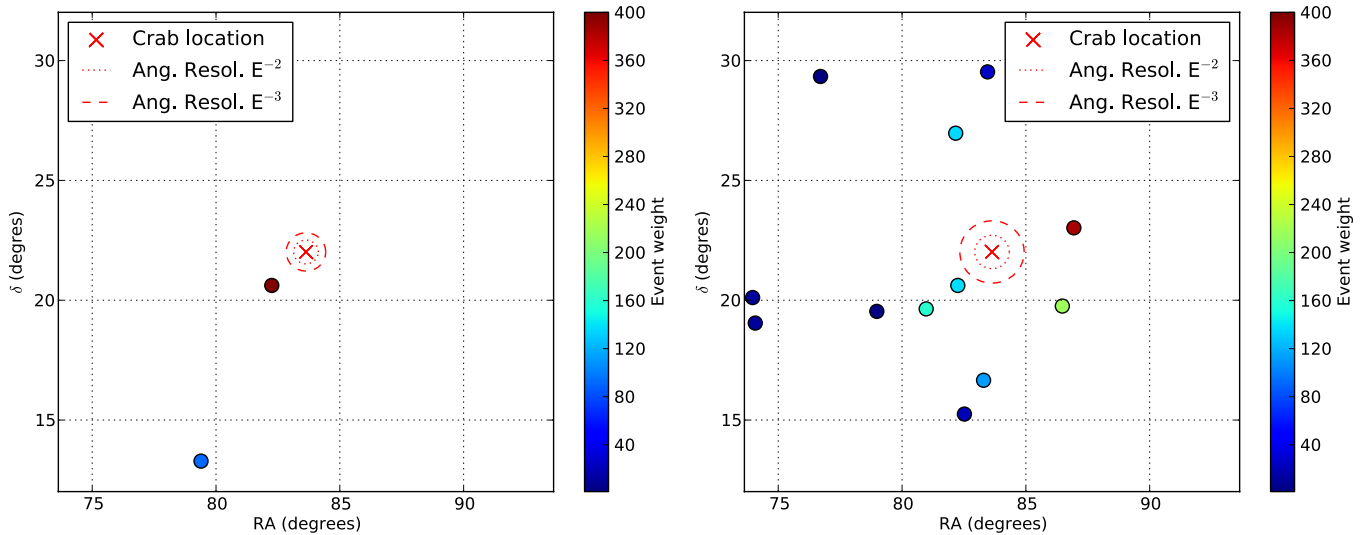


Figure 4. Left: event distribution for the straight cuts for events with $\frac{S_i}{B_i} > 1$. The color code represents the event signal-over-background ratio. Right: same distribution for the BDT sample.

(A color version of this figure is available in the online journal.)

The likelihood is then maximized with respect to n_s and γ , giving the best-fit values \hat{n}_s and $\hat{\gamma}$. The null hypothesis is given by $n_s = 0$ (γ has no meaning when no signal is present). The likelihood ratio test-statistic is defined as

$$\text{TS} = -2 \log \left[\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s, \hat{\gamma}_s)} \right]. \quad (5)$$

The background probability distribution function, or pdf, \mathcal{B}_i , is given by

$$\mathcal{B}_i = \mathcal{B}_i^{\text{space}}(\theta_i, \phi_i) \mathcal{B}_i^{\text{energy}}(E_i, \theta_i) \mathcal{B}_i^{\text{time}}(t_i, \theta_i), \quad (6)$$

and is computed using the distribution of data itself. The spatial term $\mathcal{B}_i^{\text{space}}(\theta_i, \phi_i)$ is the event density per unit solid angle as a function of the local coordinates. The energy probability, $\mathcal{B}_i^{\text{energy}}(E_i, \theta_i)$, is determined from the energy proxy distribution of data as a function of the cosine of the zenith angle, θ_i . This energy proxy, described in detail in Abbasi et al. (2011a), uses the density of photons along the muon track due to stochastic energy losses of pair production, bremsstrahlung, and photonuclear interactions which dominate over ionization losses for muons above 1 TeV. The time probability $\mathcal{B}_i^{\text{time}}(t_i, \theta_i)$ of the background can be taken to be flat for this case of a 10 day time interval ignoring the seasonal modulations.

The signal pdf \mathcal{S}_i is given by

$$\mathcal{S}_i = \mathcal{S}_i^{\text{space}}(|\vec{x}_i - \vec{x}_s|, \sigma_i) \mathcal{S}_i^{\text{energy}}(E_i, \theta_i, \gamma_s) \mathcal{S}_i^{\text{time}}(t_i), \quad (7)$$

where $\mathcal{S}_i^{\text{space}}$ depends on the angular uncertainty of the event σ_i and the angular difference between the event position \vec{x}_i and the source position \vec{x}_s . The density function $\mathcal{S}_i^{\text{energy}}$ is a function of the reconstructed energy proxy E_i , and the spectrum γ_s is calculated from an energy distribution of simulated signal in a zenith band that contains the source. The signal time probability, $\mathcal{S}_i^{\text{time}}$, depends on the particular signal hypothesis. In this analysis we adopt a simple cut in time between t_{\min} and t_{\max} , which can be expressed as

$$\mathcal{S}_i^{\text{time}} = \frac{H(t_{\max} - t_i) \times H(t_i - t_{\min})}{t_{\max} - t_{\min}}, \quad (8)$$

where t_i is the arrival time of the event, t_{\max} and t_{\min} are the upper and lower bounds of the time window defining the flare, and H is the Heaviside step function.

The significance of the result is evaluated by comparing the test-statistic with a distribution obtained by performing the same analysis over a set of background-only scrambled data sets. The fraction of trials above the test-statistic value obtained from data is referred to as the p -value, with smaller p -values indicating that the background-only (i.e., null) hypothesis is increasingly disfavored compared to the signal-plus-background hypothesis as a description of the data. This leads to the definition of the discovery potential: the average number of signal events required to achieve a p -value less than 2.87×10^{-7} (one-sided 5σ) in 50% of trials. Similarly, the sensitivity is defined as the average signal required to obtain, in 90% of trials, a test-statistic greater than the median test-statistic of background-only scrambled samples.

4. RESULTS

The method described in Section 3 has been applied to both data samples, the one obtained with straight cuts and the one obtained using the BDTs. In both cases the best fit resulted in $n_s = 0$ (i.e., an underfluctuation). Figure 4 shows the event distribution for those events with a $\frac{S_i}{B_i} > 1$, that is, only events inside the flare window that contribute to the likelihood.

As can be seen, due to its higher neutrino efficiency at energies below 10 TeV the BDT sample has more atmospheric neutrino events. Since the background estimation depends on the sample, the signal-to-background ratios are different for the same events in the two samples. The highest event weight comes from the straight cuts sample.

Table 2 shows the upper limits set by both data samples for different neutrino spectra. Each upper limit is shown both in terms of number of signal events that can be rejected at 90% confidence level (CL), $n_s^{90\%}$, and the flux limit on muon neutrinos, $\Phi_{\nu_\mu}^{90\%}$, for a 9.28 day interval in units of $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$, i.e., $\frac{dN_{\nu_\mu}^{90\%}}{dE} = \Phi_{\nu_\mu}^{90\%} \left(\frac{E}{\text{TeV}}\right)^{-\gamma}$. The limit set on the flare period of the Crab is not as competitive as the steady emission limits discussed in Section 5. Although if those limits come from a smaller

Table 2Upper Limits of the Crab 2010 September Flare Using Neyman for Both Samples and Different Neutrino Spectra Including those with an Exponential Energy Cutoff Expressed as $E^{-\gamma} \exp(-E/E_{\text{cutoff}})$ where E_{cutoff} is the Energy Cutoff

Spectrum		Straight Cuts Sample					BDT Sample				
$E^{-\gamma}$	E_{cutoff} (TeV)	$n_s^{90\%}$	$\Phi_{\nu_\mu}^{90\%}$	E_{min} (GeV)	E_{max} (GeV)	$\mathcal{L}_{\nu_\mu}^{90\%}$	$n_s^{90\%}$	$\Phi_{\nu_\mu}^{90\%}$	E_{min} (GeV)	E_{max} (GeV)	$\mathcal{L}_{\nu_\mu}^{90\%}$
E^{-2}	...	2.15	4.84	$10^{3.3}$	$10^{5.7}$	3.56	2.35	4.80	$10^{3.1}$	$10^{5.9}$	4.04
$E^{-2.7}$	...	2.41	32.6	$10^{2.6}$	$10^{4.9}$	12.0	2.90	26.3	$10^{2.3}$	$10^{4.7}$	13.5
E^{-2}	1	2.80	309	$10^{2.4}$	$10^{3.5}$	43.4	3.50	191	$10^{2.3}$	$10^{3.5}$	31.0
E^{-2}	100	2.25	8.59	$10^{3.2}$	$10^{5.0}$	3.96	2.51	8.06	$10^{2.9}$	$10^{4.9}$	4.10
E^{-2}	1000	2.20	5.52	$10^{3.3}$	$10^{5.6}$	3.58	2.34	5.31	$10^{3.0}$	$10^{5.5}$	3.72

Notes. The number $n_s^{90\%}$ is the limit in terms of number of signal events for a 90% confidence level and $\Phi_{\nu_\mu}^{90\%}$ is the flux upper limit in units of $10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ for a 9.28 days flaring interval. The resulting neutrino luminosity limit, $\mathcal{L}_{\nu_\mu}^{90\%}$, is given in units of $10^{35} \text{ erg s}^{-1}$ and it was calculated by integrating $dN^{90\%}/dE \times E$ over the energy range from E_{min} to E_{max} to contain 90% signal of the spectrum and multiplying by $4\pi d^2$ where d is the distance to the Crab Nebula ($d = 1850 \text{ pc}$). Equipartition of neutrino flavors at Earth ($\nu_e : \nu_\mu : \nu_\tau = 1:1:1$) due to neutrino oscillations has been assumed to calculate luminosities at the source.

40-string detector compared to 79 strings, they are obtained over a period of time about 30 times longer. Because IceCube is not yet in a background-limited regime the steady limits are about a factor of 10 better. As an example the flux limit for an E^{-2} spectrum during the flare emission is $4.8 \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ while the limit set on the steady emission in Abbasi et al. (2011a) is $3.7 \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$.

The analysis described and the results given in Table 2 rely on the fact that background simulation can be performed by scrambling the right ascension in real data (even if a signal is present in the data sample the scrambling will dilute it over the background). This method of estimating the background gives robust p -values in terms of systematic uncertainties. Systematic uncertainties only affect the estimate of the signal flux from the source and the upper limits. The systematic uncertainties on the expected flux come from photon propagation in ice, absolute DOM sensitivity ($\pm 8\%$), and uncertainties in the Earth density profile as well as muon energy loss. The main uncertainty, however, is the modeling of Antarctic ice and its effect on the photon propagation. In IceCube different ice models have been devised. The variations in the upper limits depending on the photon propagation model used are within $< 10\%$. Overall the uncertainty on upper limits is 16%.

5. IMPACT OF ICECUBE TIME-INTEGRATED LIMITS ON MODELS FROM THE CRAB

The main goal of the IceCube telescope is the search for cosmic neutrino signals that might explain the astrophysical phenomena that give rise to the CR emission. In the absence of detection, constraining models can also provide insights about the nature of these phenomena. The best available neutrino flux limits for the Crab are based on the time-integrated analysis performed during the 375.5 day period corresponding to the 40-string configuration of IceCube. We discuss here the impact of these limits on different models of neutrino emission from the Crab. Figure 5 summarizes a number of different predicted fluxes described in the introduction of this paper and where the 40-string configuration limits stand (Abbasi et al. 2011a). Upper limits are defined as the 90% CL using the method from Feldman & Cousins (1998). The green line (solid) corresponds to the flux predicted in Kappes et al. (2007) based on the γ -ray spectrum measured by H.E.S.S. and the corresponding upper limit (dashed). The black line represents

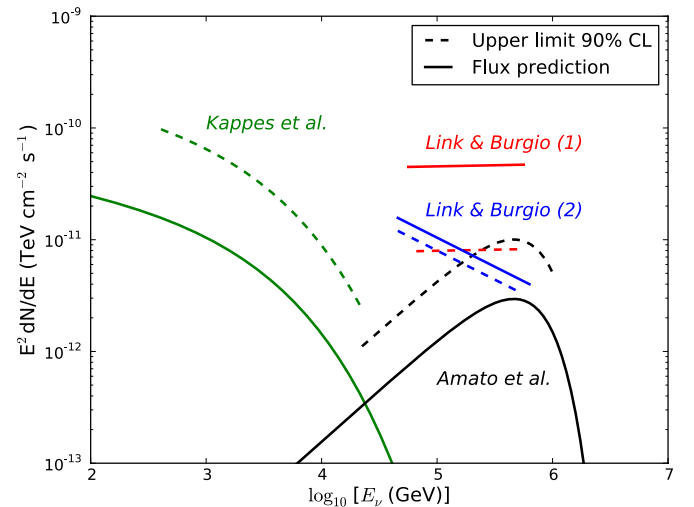


Figure 5. Predicted fluxes and upper limits based on the IceCube 40-string configuration on several models from the Crab. Solid lines indicate the predicted flux and dotted lines the corresponding upper limit for a 90% CL. The green lines are the predicted flux and corresponding upper limit based on the model proposed in Kappes et al. (2007). The red and blue lines correspond to the model in Link & Burgio (2005) for the cases of linear (1) and quadratic (2) proton acceleration. The black line represents the estimated flux for the most optimistic model proposed in Amato et al. (2003) based on resonant cyclotron absorption model and its corresponding upper limit.

(A color version of this figure is available in the online journal.)

the estimated flux based on the resonant cyclotron absorption model proposed in Amato et al. (2003) for the case of a wind Lorentz factor of $\Gamma = 10^7$ and the most optimistic case of the effective target density. The red and blue lines represent the two predicted fluxes according to Link & Burgio (2005) for the cases of linear and quadratic proton acceleration, respectively. The most optimistic version of this model can be rejected with more than 90% CL for the assumed parameters in the paper constraining some of its parameters for both forms of proton acceleration. Note that protons have been assumed but in general nuclei could be accelerated as well. According to this model, the density of the charge-depleted gap above the star is parameterized by $f_d n_0$, where n_0 is the Goldreich–Julian density of ions that depends on the magnetic field and period of the Crab that are also well known. The neutrino flux depends linearly on the charge depletion factor, f_d , which can take values between

0 and 1. The neutrino fluxes calculated according to this model shown in Figure 5 assume $f_d = 1/2$, hence we conclude that values above 0.5 are excluded at more than 90% CL. Another parameter on which the neutrino flux depends linearly is f_b or the fraction of the pulse period in which we see the radio beam. However, the value of this parameter can accurately be derived from radio measurements and we therefore take $f_b = 0.14$ for the Crab.

6. CONCLUSIONS

Searches for neutrinos in coincidence with the 2010 September Crab flare have been presented in this paper. The data used were taken with the 79-string configuration of IceCube. This is the first analysis of data taken by this configuration and represents the first rapid response analysis of IceCube to an astronomical event such as the flaring of an otherwise steady standard candle source. Two different approaches of event selection have been followed—one using direct cuts on quality reconstruction variables and optimized for discovery for E^{-2} neutrino spectra, and the other based on multi-variate analysis and optimized for discovery at lower energies, important for Galactic sources that have soft spectra with cutoffs at TeV energies. The two data sets however showed a background underfluctuation during the time interval considered. The corresponding upper limits based on generic neutrino spectra have been shown for the flaring state of the Crab.

Assuming isotropic emission from the shock (even if this may not be the case for a highly relativistic pulsar wind) our limit for E^{-2} corresponds to a neutrino luminosity constraint for the flare state of about $\sim 2 \times 10^{35}$ erg s^{-1} , and $\sim 1.5 \times 10^{36}$ erg s^{-1} if a neutrino cutoff of 1 TeV is assumed. In both cases the resulting neutrino luminosity constraint is about 2–3 orders of magnitude lower than the spin-down luminosity of the pulsar and comparable to the peak isotropic γ -ray luminosity $\sim 5 \times 10^{35}$ erg s^{-1} measured by *AGILE* (Tavani et al. 2011) in the energy range from 0.1 to 10 GeV.

In addition to the flare analysis we calculated the current best limits set by IceCube on different models for neutrino emission from the Crab Nebula. These limits are based on the time-integrated analysis of IceCube with the 40-string configuration of the detector. The upper regions of the most optimistic models can be rejected with more than 90% CL, providing useful constraints on adjustable parameters of these models. Taking the neutrino spectrum derived from the γ -ray observations from the Crab, the constraint in muon neutrino luminosity for the steady emission of the Crab is $\lesssim 2 \times 10^{35}$ erg s^{-1} which is a factor ~ 3.4 larger than the luminosity in γ -rays, assuming the γ -ray spectrum measured in Aharonian et al. (2006) integrated over the energy range between 400 GeV and 40 TeV.

In the future the IceCube detector will combine data sets from different detector configurations. When the different live times of the 40-string configuration data and the full detector are summed, the sensitivity will improve by about a factor of five, making this search more predictive.

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