Searches for neutrinos from GRBs with the IceCube 22-string detector and sensitivity estimates for the full detector

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Abstract. **This contribution presents results of searches with IceCube in its 22-string configuration for neutrinos from 41 stacked gamma-ray bursts (GRBs) detected in the northern sky by satellites like Swift. In addition, the capabilities of the full 80-string detector based on a detailed simulation are discussed. GRBs are among the few potential source classes for the highest energy cosmic rays and one of the most puzzling phenomena in the universe. In their ultra-relativistic jets, GRBs are thought to produce neutrinos with energies well in excess of 100 TeV. However, up to now, no such neutrino has been observed. IceCube, currently under construction at the South Pole, is the first km^3 scale neutrino telescope. As such it will have a significantly improved sensitivity compared to the precursor class of 0.01 km^3 neutrino telescopes.**

Keywords: **Gamma-Ray Bursts, Neutrinos, IceCube**

I. INTRODUCTION

Gamma-ray Bursts (GRBs) have been proposed as a plausible source of the highest energy cosmic rays [1] and high energy neutrinos [2]. The prevalent belief is that the progenitors of so called *long-soft* GRBs are very massive stars that undergo core collapse leading to the formation of a black hole. *Short-hard* GRBs are believed to be the product of the merger of binary compact objects such as neutrons stars and black holes leading to the creation of a single black hole. Material is ejected from the progenitor in ultra-relativistic jets. In these jets, electrons and baryons are accelerated to high energies, where the synchrotron radiation from the electrons is observed as the prompt γ-ray signal. Neutrinos are predicted to be produced in the interaction of accelerated baryons with matter or photons in various phases of the GRB: *TeV precursor*—while the jet burrows through the envelope of the progenitor of a long-soft burst [3]; *PeV prompt*—in coincidence with the observed γ-ray signal [2]; *EeV early afterglow*—as the jet collides with interstellar material or the progenitor wind in the early afterglow phase [4].

IceCube is a high energy ($E \gtrsim 1$ TeV) neutrino telescope currently under construction at the South Pole [5]. When completed, the deep ice component of IceCube will consist of 5160 digital optical modules (DOMs) arranged in 86 strings frozen into the ice, at depths ranging from 1450 m to 2450 m. Each DOM contains a photo-multiplier tube and supporting hardware inside a glass pressure sphere. The total instrumented volume of IceCube will be ~ 1 km^3. The DOMs indirectly detect neutrinos by measuring the Cherenkov light from secondary charged particles produced in neutrino-nucleon interactions. Presently, 59 strings are installed and collect data continuously. Construction is scheduled for completion by 2011. AMANDA-II, IceCube's predecessor array, operated between January 2000 and May 2009. It consisted of 677 optical modules arranged on 19 strings with an instrumented volume approximately 60 times smaller than that of IceCube. Searches with AMANDA-II for neutrinos in coincidence with GRBs have been reported with negative results [6], [7].

The two main channels for detecting neutrinos with IceCube are the muon and the cascade channels. Charged current interactions of ν_μ produce muons that, at TeV energies, travel for several kilometers in ice and leave a track-like light pattern in the detector. The detectors are mainly sensitive to up-going muon neutrinos as the Earth can be used to shield against the much larger flux of (up-going) atmospheric muons. Searches for neutrinos from GRBs in the muon channel benefit from good angular resolution ($\sim 1°$ for $E_\nu > 1$ TeV) and from the long range of high energy muons. Therefore, we use this channel in our analyses.

II. ICECUBE 22-STRING RESULTS

In our analyses, we search the IceCube 22-string configuration data, collected between May 2007 and April 2008, for muon neutrinos from GRBs in the northern hemisphere. In [8] further analyses using IceCube 22-string data are presented which extend the muon neutrino search to GRBs in the southern sky and use the cascade channel to search for neutrinos of all flavors from GRBs in both hemispheres, respectively.

We perform our searches both in the prompt (defined by the observed γ-ray emission) and the precursor (100 s before the prompt time window) time windows. In order to account for alternative emission scenarios, an additional search is conducted in an extended window from -1 h to $+3$ h around the burst. The data outside
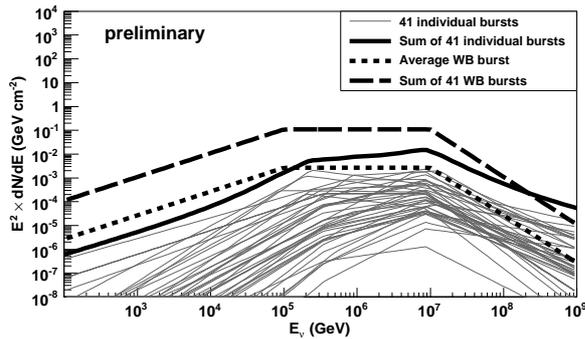
Fig. 1.   Neutrino spectra for all 41 GRBs investigated in the analyses. The fluences were calculated for each burst individually using measured bursts parameters following [11]. For comparison, average Waxman-Bahcall GRB fluences (WB, [2]) are shown.
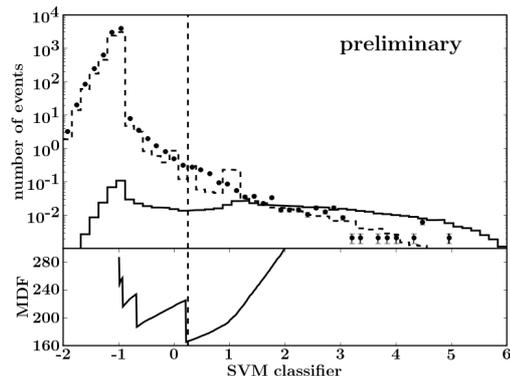

Fig. 2.   The SVM classifier distribution of off-time data, simulated backgrounds (dashed), and simulated GRB muon neutrinos (solid). The lower frame displays the MDF resulting from a cut on the SVM classifier. The vertical dashed line shows the final tightened cut at 0.25.

these windows (off-time data) is used to estimate the background in the search windows.

To prevent bias in our analyses, the data within the $-1\,\mathrm{h}$ to $+3\,\mathrm{h}$ window (on-time data) are kept blind during optimization. Only low level quantities of the on-time data are examined in order to determine stability. The remaining, usable off-time data amounts to 269 days of livetime. Of the 48 northern hemisphere bursts detected by satellites (mainly Swift [9]), 7 do not have quality IceCube data associated with them during the prompt/precursor emission windows. For all remaining 41 GRBs, tests show no indications of abnormal behavior of the detector.

As customary, we use the Waxman-Bahcall model as a benchmark for neutrino production in GRBs. The original calculation with this model [2] used average GRB parameters as measured by BATSE [10]. It was refined by including specific details for individual GRBs [11]. Our neutrino calculations follow the latter prescription. For many GRBs the available information is incomplete. In that case we use average parameters in the modeling of the neutrino flux. The individual burst neutrino spectra are displayed in Fig. 1.

Tracks are reconstructed using a log-likelihood reconstruction method [12]. A fit of a paraboloid to the region around the maximum in the log-likelihood function yields an estimate of the uncertainty on the reconstructed direction. Initially, candidate neutrino events are outnumbered (by several orders of magnitude) by downgoing atmospheric muons that are mis-reconstructed as up-going events. Application of data selection criteria allows us to extract a high-purity sample of up-going (atmospheric, and potentially astrophysical) neutrinos.

In order to determine our detector response to the expected GRB neutrinos, we simulate these signal events using ANIS [13]. Background from atmospheric muons is simulated with CORSIKA [14]. Propagation of neutrinos and muons through the Earth and ice are performed with ANIS and MMC [15]. The photon signal at the DOMs is determined from a detailed simulation [16] of the propagation of Cherenkov light from muons and showers through the ice. The simulation of the DOM response takes into account the DOM's angular acceptance and includes a simulation of the DOM electronics. The DOM output is then processed with a simulation of the trigger. Afterwards, the simulated events are treated in the same way as the real data.

A. Binned analysis

We perform a binned analysis searching for emission during the prompt phase. After a loose preselection of events, various quality parameters are combined using a machine learning algorithm. The algorithm used was a Support Vector Machine (SVM) [17] with a radial basis function kernel. The SVM was trained using the off-time filtered data as background and all-sky neutrino simulation weighted to the sum of the individual burst spectra as signal. The optimum SVM parameters (kernel parameter, cost factor, margin) were determined using a coarse, and then fine, grid search with a 5-fold cross validation technique at each node [18].

The resulting SVM classification of events is shown in Fig. 2. The final cut on this parameter is optimized to detect a signal fluence with at least 5σ (significance) in 50% of cases (power) by minimizing the Model Discovery Factor (MDF). The MDF is the ratio between the signal fluence required for a detection with the specified significance and power and the predicted fluence [19]. The angular cut around each GRB is then calculated to keep 3/4 of the remaining signal after the cut on the SVM classifier. In this way, there is one cut on the SVM classifier for all GRBs, but different angular cuts around each GRB according to the angular resolution of the detector in that direction. The SVM cut that returns the best sensitivity is at 0.22. This cut lies directly on a discontinuity in the MDF curve, and so it is tightened away from that discontinuity so that a 1σ underestimation of the background level will not lead to a discovery claim more significant than is appropriate.

B. Unbinned likelihood analysis

We compare the performance of the binned analysis for the prompt emission to that of an unbinned likelihood

analysis. Furthermore, we use the unbinned method to look for neutrino emission in the precursor and extended time window. The unbinned method used here is similar to that described in [20]. The signal, $S(\vec{x}_i)$, and background, $B(\vec{x}_i)$, PDFs are formed from a product of a directional, time and an energy PDF.

Signal PDF: The directional signal PDF is a two-dimensional Gaussian distribution with the two widths being the major and minor axes of the 1σ error ellipse of the paraboloid fit. The time PDF is flat over the respective time window and falls off on both sides with a Gaussian distribution of variable width depending on the duration of the emission. The energy PDF is determined from the distribution of an energy estimator [21] for each GRB individually. The signal PDFs of the GRBs are combined using a weighted sum [22]

$$S_{\text{tot}}(\vec{x}_i) = \frac{\sum_{j=1}^{N_{\text{GRBs}}} w_j \, S_j(\vec{x}_i)}{\sum_{j=1}^{N_{\text{GRBs}}} w_j} \ , \qquad (1)$$

where $S_j(\vec{x}_i)$ is the signal PDF of the jth GRB and w_j is a weight that for of the prompt and precursor window is proportional to the expected number of events in the detector according to the calculated fluences. In the case of the extended window we use $w_j = 1$ for all GRBs.

Background PDF: For the directional background PDF obtained from the off-time data, the detector asymmetries in zenith and azimuth are taken into account by evaluating the data in the detector coordinate system. The time distribution of the background during a GRB can be assumed to be constant, yielding a flat time PDF. The energy PDF is determined in the same way as for the signal PDF with the spectrum corresponding to the Bartol atmospheric neutrino flux [23].

All PDFs are combined in a log-likelihood ratio

$$\ln(\mathcal{R}) = -\langle n_s \rangle + \sum_{i=1}^{N} \ln \left(\frac{\langle n_s \rangle \, S_{\text{tot}}(\vec{x}_i)}{\langle n_b \rangle \, B(\vec{x}_i)} + 1 \right) \quad (2)$$

where the sum runs over all reconstructed tracks in the final sample. The variable $\langle n_b \rangle$ is the expected mean number of background events, which is determined from the off-time data set. The mean number of signal events, $\langle n_s \rangle$, is a free parameter which is varied to maximize equation 2 in order to obtain the best estimate for the mean number of signal events, $\langle \hat{n}_s \rangle$.

To determine whether a given data set is compatible with the background-only hypothesis, 10^8 background data sets for the on-time windows are generated from off-time data by randomizing the track times while taking into account the downtime of the detector. For each of these data sets the $\ln(\mathcal{R})$ value is calculated. The probability for a data set to be compatible with background is given by the fraction of background data sets with an equal or larger $\ln(\mathcal{R})$ value.

The analysis is performed on a high-purity up-going neutrino sample after tight selection criteria have been applied. The unbinned likelihood method requires an ~ 1.8 times lower fluence for a 5σ detection than the
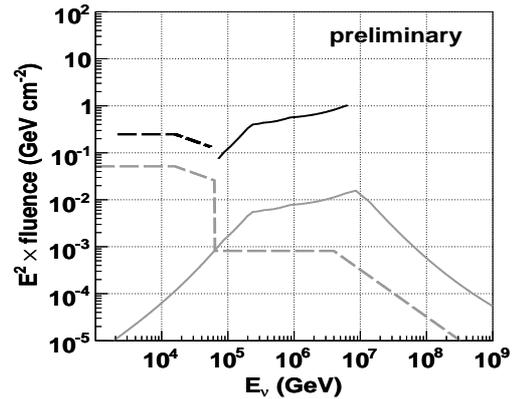

Fig. 3. Light lines—Predicted fluences from the 41 northern hemisphere GRBs for different emission models: prompt (solid, sum of individual spectra as plotted in Fig. 1) and precursor (dashed, [3]). Dark lines—90% C.L. upper limits on the neutrino fluences obtained with the unbinned likelihood analysis.

binned method. The former is therefore used for the results presented in this paper.

The unblinding procedure involves applying the likelihood method to the on-time data set after neutrino candidate event selection. For all three emission scenarios the best estimate for the number of signal events ($\langle \hat{n}_s \rangle$) is zero and hence consistent with the null hypothesis. Figure 3 displays preliminary 90% C.L. upper limits for the 41 GRBs on the fluence in the prompt phase (sum of individual spectra as plotted in Fig. 1) of $3.7 \times 10^{-3}\,\text{erg}\,\text{cm}^{-2}$ (72 TeV – 6.5 PeV) and on the fluence from the precursor phase [3] of $1.16 \times 10^{-3}\,\text{erg}\,\text{cm}^{-2}$ (2.2 TeV – 55 TeV), where the quoted energy ranges contain 90% of the expected signal events in the detector. The limits obtained are not strong enough to constrain the models. The preliminary 90% C.L. upper limit for the wide time window is $2.7 \times 10^{-3}\,\text{erg}\,\text{cm}^{-2}$ (3 TeV – 2.8 PeV) assuming an E^{-2} flux.

III. IceCube Sensitivity study for the full detector

Previous studies have estimated the sensitivity of the completed IceCube to neutrino fluxes from GRBs [24], [25]. We present new results using updated information about the detector, improved simulation, and more accurate calculation of the backgrounds.

We utilize the same methods as in the 22-string search to study the sensitivity of the full 86 string detector. We generate a set of fake GRBs by sampling from the populations observed by the Swift [9] and Fermi [26] satellites and taking their observation rates into account. We distribute these bursts isotropically over the sky and randomly in time to produce a set of 142 fake GRBs in the northern sky for a detector livetime of one year, with 6840 s of total emission during the prompt phase. Currently, we use the average Waxman-Bahcall GRB neutrino flux for all bursts [2]. In the future, it will be replaced by individual spectra. To test the precursor phase, we assume each burst has such emission [3]
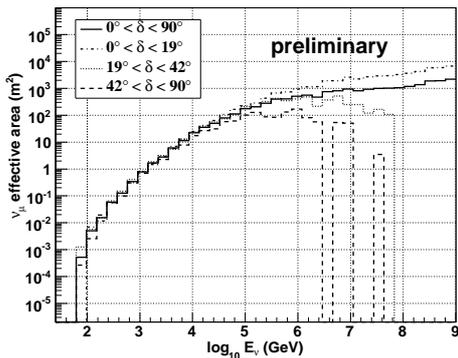
Fig. 4.   Muon neutrino effective area for the full IceCube detector as a function of energy. Solid line is averaged over the half sky, while dot-dashed, dotted, and dashed lines represent the most horizontal, middle, and most vertical thirds of the northern sky in $\cos\delta$, respectively.

lasting for $100\,\mathrm{s}$ immediately preceeding the observed photons.

As no off-time data is available to determine the background, it is simulated. Atmospheric muons and neutrinos are generated over the full sky and propagated to the detector in the same manner as outlined in section II. The geometry of the full detector is simulated in determining the response to Cherenkov photons. Signal and background are filtered with cuts on quality parameters to create a sample of well-reconstructed, seemingly upgoing events. Further event selection with a machine learning algorithm [27] is then performed to remove the remaining misreconstructed downgoing muons. Afterwards, no atmospheric muons remain in the sample due to the limited amount of Monte Carlo. As no real data is available for comparison, the exact purity of the remaining background sample is unknown, but is estimated to consist of $> 95\%$ atmospheric neutrinos below the horizon, while retaining a large fraction of GRB signal neutrinos. The effective area for different declination bands is shown in Fig. 4. Given the detector angular resolution of $\sim 1°$, we select a search bin radius of $2°$ around each fake GRB location, retaining 70–90% of signal neutrinos (depending on declination) while dramatically reducing the isotropic background rate. The background is then rescaled to match the emission time window for each burst.

First results of this study indicate that we will be able to detect neutrinos from GRBs in either phase at the 5σ level in greater than 90% of potential experiments within the first few years of operating the full detector. In the event of non-detection, we will be able to set strict upper limits well below the fluences predicted by these models.

IV. Conclusions

We have presented results of searches for muon neutrinos from GRBs with the 22-string configuration of the IceCube detector. These searches covered several time windows corresponding to the various phases of the predicted emission. In all cases, the data were consistent with the background only hypothesis. Hence, we place upper limits on the muon neutrino fluences from the different phases, which, however, are not tight enough to constrain any model yet.

We are also performing a detailed sensitivity study for the full 80-string IceCube detector. The preliminary results of this study show that IceCube will be able to detect the neutrino flux predicted by the leading models with a high level of significance within the first few years of operation or, in the event of no observation, place strong constraints on emission of neutrinos from GRBs.

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