Search for TeV electron neutrinos from Gamma Ray Bursts with the ARGO−YBJ experiment

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Abstract: The capability of the ARGO-YBJ experiment to detect Horizontal Air Showers (HAS) has been recently emphasized. More than 10^7 showers at zenith angles $\theta > 70^\circ$ have been recorded in five years of operation. These showers are initiated by deeply penetrating high energy particles such as muons and neutrinos. Indeed, at large zenith angles the electromagnetic component of ordinary air showers is attenuated by the atmosphere well before reaching the ground level. Due to its features (a compact 92% active area equipped with a high-granularity readout) the ARGO-YBJ detector can image small size air showers induced by particles with energies down to a few TeV. We report here on a search for ν_e-induced HAS ($73^\circ \leq \theta \leq 77^\circ$) in temporal coincidence with the prompt phase of Gamma Ray Bursts.

Keywords: Electron neutrinos, Gamma Ray Bursts, ARGO-YBJ experiment.

1 Introduction

Despite the observation by several experiments, the origin of Ultra High Energy Cosmic Rays (UHECRs) with energies above 10^9 GeV remains not well understood. Being amongst the most violent events in the universe, Gamma Ray Bursts (GRBs) have been proposed as a powerful accelerator of UHECRs. The particle acceleration is thought to occur both in internal or external shocks. The leading model involves a plasma flow accelerated to relativistic speeds. In the main accepted scenario, protons accelerated to ultra high energies in internal shocks of relativistic jets interact with the surrounding radiation field producing neutrinos ν in the TeV-PeV domain. Due to ν vacuum oscillations, a flavour ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at Earth is expected for ν produced in a distant source[1].

However, severe limits have been fixed by the IceCube observations which constrain the ν_μ flux associated to GRBs to below the expectations based on the paradigma that GRBs are the sources of the UHECRs. The internal shock model is severely challenged [3]. Reduction of the ν flux at source [4], different models [5] or different evolution of the ν flavour ratio during their flight to Earth [6] have been envisaged to explain the negative result reported by the IceCube collaboration. Fluence upper limits on high energy ν_τ associated to GRB have been recently published by the Ashra experiment [7]. This is a telescope devoted to the detection of Cherenkov photons in air showers induced by the decay of the tau leptons resulting from the interaction of ν_τ with the Manua Kea volcano on Hawaii Island.

The aim of the present analysis of the ARGO-YBJ data is the search for prompt ν_e produced in GRBs looking at horizontal air showers (HAS) induced by the charged current (CC) interaction of these ν with the air nuclei. This search provides a complementary channel to muon detection by IceCube or photon detection as implemented in the Ashra experiment. 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 ν energy, about 50% at low energies, rising to 75% above 100 TeV [1]. These electrons promptly initiate an electromagnetic cascade that can be detected if the ν interaction point is at the appropriate distance from the ARGO-YBJ array. 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. Hence, also due to the quite small active area of the ARGO-YBJ detector, we can anticipate that the effective volume achieved with this method ($\leq 10^{-5}$ the IceCube effective volume) is not enough to reach the sensitivity of the other techniques. However, there are many reasons to pursue also this approach.

The expected ν flux can vary by order of magnitude between GRBs due to the fluctuations in the burst parameters and several GRBs in the ARGO-YBJ data set are not included in the IceCube list. Moreover, core-collapse supernovae (SNe), which are believed to be the origin of long-duration (>2 s) GRBs, could produce ν bursts in events in which mildly relativistic jets interact inside the stellar envelope. The ν spectrum produced in these events (as, for instance, the "choked GRBs" [8]) is expected softer but very high in fluence. The ARGO-YBJ detector, character-

1. A 20% fraction of $\overline{\nu}_e$ is expected. However, taking into account the charged current cross section and the average energy transferred to the positron [1], a pure ν_e beam implies an overestimation of the expected signal of about 10% [2].

ized by a compact active area (92%) with high-granularity readout, is well suited to image showers at energies down to the sub-TeV range. Finally, it is important to define algorithms and procedures that could be exploited in future searches with very large size and dense sampling arrays like the LHAASO project [9].

Cascade events are also produced in ν_μ 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 ν 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 ν flavours can generate cascades via the Neutral Current (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 ν flux with the energy. Moreover, the energy deposited in the hadronic jet, less than 50% that of the ν, can be shared by more than one particle.

2 The ARGO−YBJ experiment

The ARGO-YBJ detector, located at the Yangbajing Cosmic Ray Laboratory (Tibet, China) at an altitude of 4300 m above the sea level, consists of a 74×78 m^2 carpet made of a single layer of Resistive Plate Chambers (RPCs) with about 92% of active area, sorrounded by a partially instrumented (about 20%) area up to 100×110 m^2. Each RPC is read by 80 strips of 6.75×61.8 cm^2 (the spatial pixels), logically organized in 10 independent pads of 55.6×61.8 cm^2 which represent the time pixel of the detector. ARGO-YBJ is operated with an inclusive trigger based on a time correlation between the pad signals, depending on their relative distance. The shower reconstruction method is described in [10]. The index of the measured strip spectrum increases with the zenith angle up to about 70° where we observe a sharp transition to a spectral index of about -3.6 (see Fig. 1), a typical value characterizing the spectrum of the EAS muon component. More than 10^7 HAS (zenith angle $\theta > 70°$) have been recorded in about 5 years of data taking [11]. A few HAS with more than 500 fired strips are shown in Fig. 2. A preliminary MonteCarlo simulation using the horizontal muon spectrum supports the interpretation of these showers as events induced by the interaction in atmosphere of single muons. According to this simulation, an angular resolution of about 2.3° is obtained for events with $73° \leq \theta \leq 77°$ and core landing on the detector (Fig. 3).

3 Expected events and measured background

Since the interaction length of ν in the atmosphere is larger than the whole atmospheric depth, they have practically equal probability to interact at any point in the atmosphere. The interaction length for the ν-nucleon interaction is given by $\lambda = 1/(\sigma \cdot N_A)$, where N_A is Avogadro's number and σ is the charged current ν-nucleon cross section. The energy distribution of the electrons produced is peaked near

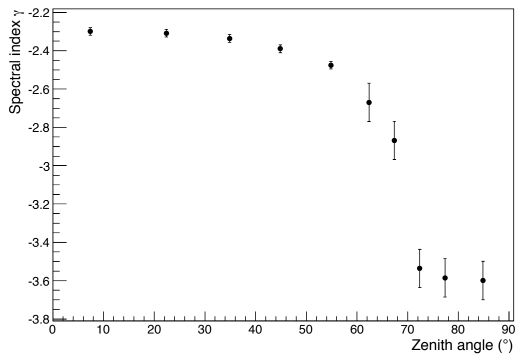

Fig. 1: Index of the measured strip spectrum as a function of the zenith angle.

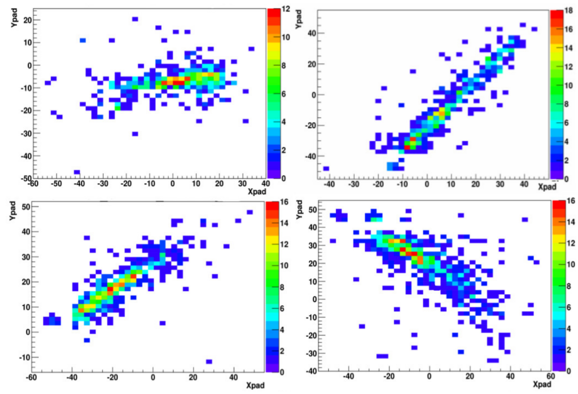

Fig. 2: Examples of HAS footprints observed with >500 strips fired on the ARGO−YBJ central carpet. The colour palettes give the number of hits in each pixel (4 × 4 pads).

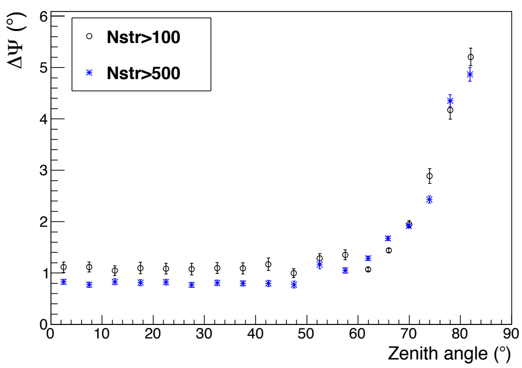

Fig. 3: Angular resolution for $N_{strip} > 100$ (circles) and $N_{strip} > 500$ (asterisks) as a function of the zenith angle.

$E_e = E_\nu$, the peak increasing with the ν energy. Electrons promptly convert into an electromagnetic shower. Showers produced at the slant depth $x(g/cm^2)$ from the array can be detected only if they are large enough to satisfy the trigger conditions and if a minimum number of fired pads is recorded to assure the needed pointing accuracy in the reconstruction of the shower direction. Then, for a given ν direction and impact parameter on the ground, the effective depth interval is basically the range of positions of the interaction point from which showers firing $N_{strip} > N_0$ are generated. In the present analysis, in order to save computing time, we only take into account showers with core landing on a fiducial area $A_f = 72m \times 75m$ internal to the detector surface. Horizontal air showers with core on the detector surface exhibit a typical configuration with a pattern elongated along the reconstructed direction of arrival, as shown in Fig.2. In this case the effective volume for ν interaction is given by $A_f \cdot \cos\theta \cdot D_{eff}$, where D_{eff} is the effective slant depth. Clearly, this choice reduces the exposure to large size showers with core falling outside the detector, showers that can be imaged by ARGO-YBJ and efficiently reconstructed [10]. The number of ν-induced showers with more than N_0 strips is given by:

$$N_{ev}(>N_0) = A_f \cdot \cos\theta \int dE_\nu \frac{dF(E_\nu)}{dE_\nu} P(E_\nu; > N_0) \quad (1)$$

where $dF(E_\nu)/dE_\nu$ is the ν energy spectrum and $P(E_\nu; > N_0)$ is the probability that a ν of energy E_ν can generate a shower with core inside the area A_f and a number of charged particles firing more than N_0 strips. The ν-shower conversion probability $P(E_\nu; > N_0)$ is obtained by a full simulation in which we use the cross section for the CC ν interaction given in [1] with the CTEQ4-DIS parton distribution, while the shower development is handled by the CORSIKA code and the detector response is simulated with the ARGOG package based on the GEANT3 code.

For the present model-driven analysis we use the Waxman & Bahcall double broken law spectrum as a reference hypothesis, that is, $dF(E_\nu)/dE_\nu = K(E/10^5 GeV)^{-\gamma}$, with γ=1 for $E < E_1$ and γ=2 for $E_1 < E < E_2$. The first break energy E_1 corresponds to the break in the parent photon spectrum, the second at very high energy E_2 comes from synchrotron losses of muons and pions. For the standard Waxman & Bahcall spectrum with the Lorentz boost factor $\Gamma = 300$ of the GRB jet, we have $E_1 = 10^5$ GeV and $E_2 = 10^7$ GeV and $K = 3 \cdot 10^{-9} GeV^{-1} m^{-2}$ [12].

Air showers generated by muon radiative processes are indistinguishable from the ν-induced showers and represent the background for this search. The background events do not need to be simulated, their rate is measured using the off-time windows where no signal is expected. We obtain mean values integrating in time and azimuth on the whole data collected at zenith angles $73° \leq \theta \leq 77°$. This allows a precise experimental determination of the background rate with a negligible statistical error. ARGO−YBJ exhibits an excellent stability [13] and both on-time and off-time tests have been carried out to check the normal behaviour of the detector during the GRB events. A mild azimuthal modulation of about 1.5% is observed in the data up to $\theta = 60°$, well explained as the combination of geomagnetic deflection and detector effects due to its geometry [14]. A larger modulation is found for reconstructed events with $\theta > 70°$. Indeed, HAS are produced by muons which travel long distances (about 120 km at $\theta = 75°$ [15]), with a non-negligible geomagnetic deflection. For the present work, addressed to a stacking analysis, we have neglected the small deviations from the quoted average values. A systematic uncertainty $< 10\%$ can be estimated to take into account this approximation.

GRB	T_0 (UT)	T90 (s)	θ (deg)	z	IC
080205	07:55:51	106.5	73.4	–	n
080413	02:54:19	46	74.1	2.43	y
080613	09:35:21	30	76.0	–	y
080625	12:28:31	80	73.8	–	y
080925	18:35:55	29	73.9	–	y
081221	16:21:11	34	73.1	2.26	y
090112B	17:30:15	12	76.9	–	y
090113	18:40:39	9.1	75.5	1.75	y
090227	07:25:57	50	73.3	–	y
090323	00:02:43	150	74.1	3.57	y
090427	23:26:27	15	74.1	–	y
090610B	17:21:32	202.5	76.0	–	y
090625	05:37:00	51	74.6	–	y
090701	05:23:56	12	75.5	–	y
090915	15:35:36	8	74.8	–	y
100213B	22:58:34	48.0	73.0	–	y
100331B	21:08:38	30	75.7	–	y
100425A	02:50:45	37.0	72.3	1.76	y
100906A	13:49:27	114.4	73.4	1.73	n
100915B	05:49:38	4	75.0	–	n
110529A	00:48:43	0.41	75.0	–	n
110708A	04:43:22	50	75.2	–	n
120602A	05:00:01	54	75.3	–	n
120712A	13:42:27	14.7	74.6	4.17	n
120803B	11:06:06	37.5	74.3	–	n
121201A	12:25:42	85	76.8	3.39	n

Table 1: List of GRBs with zenith angle $73° \leq \theta \leq 77°$ (November 2007 - January 2013) in the ARGO−YBJ field of view.

4 The GRB sample

ARGO-YBJ has been operational in its final configuration from November 2007 until January 2013 with a duty cycle greater than 86%. During this data taking time 436 GRBs occurred in the detector field of view ($\theta < 90°$), of which 148 at $\theta > 70°$. In order to avoid "edge" effects and any interference from the surrounding mountains, we restrict our analysis to the 32 GRBs exploded in the angular window $73° \leq \theta \leq 77°$, well inside the horizontal range where the soft component of proton-induced showers is completely absorbed. Considering the periods of inactivity or malfunction of the detector, data are available for 26 of these GRBs, which are listed in Table 1, where some of their properties[2] are reported, including the start time T_0, the duration T90 of the prompt phase emission, and, if measured, the redshift z. Only GRB110529A is of the short type (T90≤2 s), and 9 of these GRBs are not included ("n" in the last column) in the catalog used in the IceCube (IC) analysis.

5 Analysis results

In order to search for prompt ν-induced showers from the selected GRBs, we opened a cone with a 4.0° radius centered on the GRB positions. The angular window is determined by the ARGO−YBJ angular resolution taking into

2. taken from the GCN Circulars Archive at http://gcn.gsfc.nasa.gov/gcn3_archive.html.

account a possible slight non-collinearity of the produced electron with respect to the ν direction. About 70% of the signal is expected in this search cone. Since the spectrum of the background showers is softer than that predicted for the ν-induced showers, the choice of the threshold N_0 is crucial to improve the signal to background ratio. In this preliminary analysis this optimization has not been carried out and a threshold $N_0 = 500$ has been set. This cut assures an easy recognition of the elongated shape of the shower pattern, a high quality shower reconstruction and a very low level of the background rate, $N_{bkg}(>500) = 2.0 \cdot 10^{-3} ev/s$. With this integral analysis the median energy of the sampled ν spectrum is about 300 TeV. No event is found in the 26 signal time windows T90 of the GRBs listed in Table 1, so we find no evidence for ν-induced cascades in coincidence with the prompt phase of these GRBs. The expected number of background events in the total on-time window is 2.6±0.3. Assuming that the sum of all GRB spectra follows the Waxman-Bahcall model, a stacked analysis has been performed. Converting the upper limit obtained by using the unified Feldman & Cousins [16] approach to a fluence limit from 26 standard Waxman-Bahcall bursts, we obtain the black line shown in Fig. 4.

The uncertainties in both background (10%) and signal expectation (7%, mainly due to the limited statistics of the simulation) are not included. This measurement extends the search to the TeV region but the upper limit lies a factor $\simeq 5 \times 10^5$ above the Waxman-Bahcall prediction, hence does not allow us to constrain the model.

This study shows the capability of ARGO−YBJ to image small size HAS from TeV ν, the main limitation of this detection being the small conversion probability, about 10^{-9} in this energy range for the quoted selections. Baryon-rich mildly relativistic jets could interact inside the stellar envelope while still burrowing their way out of the star and before successfully escaping to produce a GRB. This kind of jets could be quite common in type II SNe and source of high fluence bursts of TeV ν [17].

6 Conclusions

A search for HAS produced by ν_e associated in time and space with the prompt phase of 26 GRBs has been carried out using the ARGO-YBJ data collected from Novembre 2007 to January 2013. Some of these GRBs are not included in the list of those observed by IceCube. The search has been conducted in a model-dependent way based on the Waxman-Bahcall power law spectrum taking into account the CC ν interaction with the atmosphere nucleons. A stacked analysis has been carried out to calculate an upper limit in the energy range 6 TeV−6 PeV to the ν_e fluence from the whole burst population. Thus this result (slightly conservative since we neglected other interaction channels inducing atmospheric showers) is complementary to that of IceCube, which is obtained at energies >80 TeV. However, our 90% confidence level (c.l.) upper limit rejects a flux many orders of magnitude larger than the prediction of the Waxman-Bahcall prompt emission model (Fig. 4). The sensitivity of this approach is limited by the reduced dimension of the effective volume. Indeed, apart from the small size of the ARGO-YBJ detector, there is an intrinsic limitation due to the short longitudinal development of the shower soft component. However, two interesting features emerge from this analysis. Firstly, the capability of reaching TeV energies by imaging small size showers with a sufficiently dense array, and then the low level of the background mainly due to the radiative processes of horizontal atmospheric muons whose spectrum decreases as $E^{-3.6}$. 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 ν spectrum with a fluence at TeV energies a few orders of magnitude greater than that characterizing the GRBs observed in γ-rays.

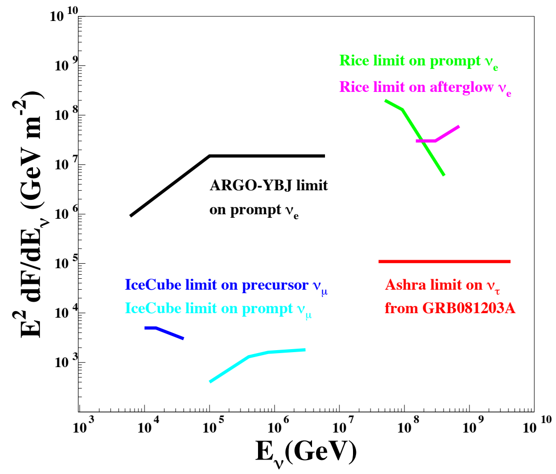

Fig. 4: 90% c.l. upper limits on the ν fluence for different experiments and GRB phases.

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