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Stacking search for neutrinos from gamma-ray bursts with the KM3NeT/ARCA detector

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Gamma-ray bursts (GRBs) are intense transient phenomena occurring at a rate of about one per day, and are considered promising candidate sources of cosmic neutrinos in the GeV-PeV energy range. Despite extensive efforts, no correlation between neutrinos and GRBs has been observed so far, motivating more exhaustive searches in a multi-messenger context.
In this contribution, a stacking search for neutrinos in spatial and time correlation of GRBs is presented, using data from the KM3NeT/ARCA detector. The detector, currently under construction at the bottom of the Mediterranean Sea, is already operational with partial configurations. This analysis employs data collected with the KM3NeT/ARCA 21 lines configuration, representing nearby 10% of the complete detector. The search is based on methods originally developed for real-time analyses, incorporating refined calibrations, dynamic positioning and enhanced event selection criteria. No significant excess of candidate neutrino events coming from the population inspected of GRBs has been observed. The results include significance estimations from the GRB locations inspected, highlighting the potential of KM3NeT/ARCA to perform dedicated multi-messenger studies.

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1. Stacking of gamma-ray bursts

Gamma-ray bursts (GRBs) are intense transient electromagnetic phenomena recognised as some of the most energetic events in the Universe. They are characterised by an initial flash of gamma-rays (the prompt phase), often followed by an afterglow emission in X-rays, optical and even radio wavelengths, lasting from days to weeks. GRBs are broadly classified into two main categories based on their origin: short GRBs (with a typical duration below two seconds), corresponding to the merger of very compact objects such as neutron star binaries or neutron star-black hole binaries, and long GRBs (typically over two seconds), attributed to the collapse of very massive, fast-rotating stars [1].

Cosmic neutrinos in temporal and spatial coincidence with GRBs have not been observed to date. However, there are several theoretical models predicting high-energy neutrino emission (usually in the TeV-PeV energy range) from these events. The most extended scenario involves the decay of charged hadrons, such as pions or kaons, produced by the interactions of protons accelerated within the relativistic outflow generated during the explosion [2].

GRBs are frequent events; on average, about one GRB per day is detected by satellite instruments such as Fermi [3] or Swift [4]. This abundance motivates stacking neutrino searches, where several GRBs are inspected over different time windows. Stacking is a statistical procedure aiming to enhance the significance of a potential observation of neutrinos. By simultaneously analysing a population of similar sources, stacking can increase the signal-to-noise ratio of the search, especially in the case of very faint emissions.

In this contribution, a stacking search for neutrinos from GRBs is presented, using data taken by the KM3NeT/ARCA neutrino telescope in the configuration with 21 detection lines. The search is done using a procedure originally developed for the real-time follow-up of individual GRB events, which has been adapted to perform a stacking search over the GRBs occurring during the time period covered by the data taken. Separate searches are conducted for long and short GRBs.

2. KM3NeT

KM3NeT [5] is an international scientific collaboration currently deploying a deep-sea infrastructure in the Mediterranean Sea. Its primary objective is the identification of the Cherenkov light emitted by particles resulting from the neutrino interactions near the detectors. Two distinct detector arrays are are being constructed: ORCA, located 40 km off Toulon (France) at a depth of 2.5 km, and ARCA, positioned at 100 km off Portopalo di Capo Passero (Sicily, Italy) at a depth of about 3.5 km. The detectors are three-dimensional arrays of photomultiplier tubes (PMTs), housed in pressure-resistant spheres known as Digital Optical Modules (DOMs) [6]. Each DOM incorporates 31 PMTs, a design offering several advantages with respect to the single-PMT design, such as the identification of physical signals through coincident hits (PMT pulses) on the same DOM. The DOMs are grouped in vertical lines known as Detection Units (DUs), each containing 18 DOMs. While both ARCA and ORCA use the same technology, their main difference lies in the spacing between the DOMs. The high DOM density design of ORCA enables search for neutrinos in the GeV energy range, while the lower DOM density of ARCA allows the search for neutrinos in sub-TeV up to PeV energies.

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Currently, 33 DUs are installed at the ARCA site, and 28 at the ORCA detector. A key feature of large-volume neutrino telescopes is the ability to acquire data even in partial configurations, enhancing the signal-to-noise ratio as new DUs are deployed. The analysis presented in this contribution employs the complete dataset of the partial ARCA detector with 21 DUs (ARCA21 hereafter), in operation from late September 2022 until early September 2023, when additional DUs were deployed. The dataset incorporates improved calibrations, providing significant enhancements over the real-time search data, including an acoustic dynamic determination of the location of the DOMs [7].

3. GRB catalog

The catalog of GRBs to be inspected has been constructed considering the data-taking period of the ARCA21 detector. Only GRBs with an earliest trigger time (T_0) falling between September 25th, 2022, 19:00:00 UTC and September 11th, 2023, 12:00:00 UTC have been included, corresponding to the full ARCA21 data acquisition period. The livetime of the ARCA21 detector during this time interval has been estimated to be about 292.2 days, representing an overall data-taking efficiency of $\sim 83\%$. GRB events for which there is not enough data in the search time window to perform the analysis have been excluded from the catalog.

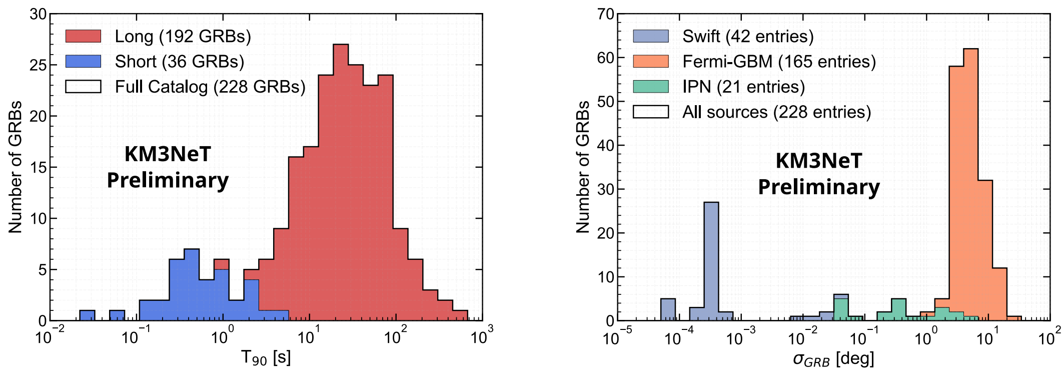
The selection of GRBs has been done by cross-referencing the data in the updated versions of the Fermi GBM Burst Catalog [3], the Swift-BAT GRB Catalog [4], the General Coordinates Network [8] and the online tool `GRBweb` [9]. The values of the most relevant parameters for the analysis are extracted from these catalogs, namely the earliest trigger time T_0, the location of the GRB in the sky in terms of declination δ and right ascension α, the angular uncertainty $\sigma_{\rm GRB}$ in the position (corresponding to a 39.3% containment assuming a two dimensional Gaussian distribution) and the duration T_{90}, defined as the time interval during which 90% of the total observed photon counts have been observed.

The complete catalog of analysed GRBs comprises 228 entries. For the case of long GRBs, 192 events have been considered, corresponding to a 94% of all the long GRBs taking place during the complete time interval (i.e., irrespective of the livetime of the detector). For short GRBs, 36 events have been inspected, representing a 78% of the GRBs available during the complete period. The selection includes the bright GRB221009A, a long GRB for which a dedicated analysis searching for neutrino emission was already conducted using KM3NeT data, with no significant neutrino detection [10].

Figure 1a presents the T_{90} distribution for the GRBs in the catalog; a clear distinction in the population of short and long GRBs can be observed at around 2 seconds. Figure 1b illustrates the $\sigma_{\rm GRB}$ distribution for the selected GRBs. The selection includes very well localised GRB events ($\sim 0.001^\circ$, corresponding to Swift events), as well as others with larger location uncertainties (up to the order of tens of degrees). The median angular uncertainty of the catalog is approximately $\sim 3.7^\circ$.

4. Search method

The search method is based on a standard binned ON/OFF technique [11], originally developed for real-time searches. The ON region is defined as the area of the sky where the signal is expected,



(a) **(b)**

Figure 1: Distributions for the T_{90} (left) and angular uncertainty on the location (right) for the GRBs considered. The latter has been split according to the instrument that performed the observation of the GRB.

while the OFF region is used to estimate the expected background in the ON region. Different elevation bands are employed as OFF regions to account for the dependence of the atmospheric background on elevation. Once the number of events in each OFF band, $N_{\rm OFF}$, has been determined, the expected background in the ON region is computed as

$$n_{\rm BKG} = \sum_{i}^{\rm bands} \frac{T_{\rm ON}}{T_{\rm OFF}} \frac{\Omega^i_{\rm ON}}{\Omega^i_{\rm OFF}} N^i_{\rm OFF} \,, \tag{1}$$

where Ω and T represent the solid angle and time window covered by the ON and OFF regions, respectively. The summation over OFF region bands takes into account the movement of the source across the local sky during the ON time window.

For the time window used to search for the signal, a model-independent approach has been followed. Standard values for the ON region time window have been defined a priori: for the stacking of short GRBs, a signal time window of $T_0 \pm 500$ seconds has been used, while for long GRBs, an extended period of $T_0 \pm 1$ day has been used. Similar time windows are also used in other KM3neT neutrino searches, such as the stacking of FRB events [12]. For the OFF region, a period of two weeks of data preceding or following the ON region time window has been considered for each individual analysis, to ensure similar data-taking conditions. Only OFF region data samples with a similar event rate as the case of the ON region have been used, ensuring stability conditions for the determination of the expected background.

The ON region is defined as a circular region centred on the position of the GRB. To determine the radius of the ON region, two systematic effects are considered in addition to the positional uncertainty of the GRB detection: the median angular resolution of the KM3NeT ARCA21 events ($\sigma_{\rm PSF}$) and the absolute pointing systematic of the detector ($\sigma_{\rm pointing}$). The radius $\sigma_{\rm RoI}$ for the ON region (or Region of Interest, RoI) is determined as

$$\sigma_{\rm RoI} = \sqrt{\sigma^2_{\rm GRB} + \sigma^2_{\rm PSF} + \sigma^2_{\rm pointing}} \,, \tag{2}$$

where $\sigma_{\rm GRB}$ denotes the angular uncertainty on the GRB event location.

The angular resolution of the ARCA21 events has been determined from Monte Carlo simulations. The Point Spread Function (PSF), defined as the probability density function of the angle between the simulated neutrino direction and the reconstructed muon direction, has been obtained for the event selection used in this stacking analysis. The median angular resolution of the events has been determined to be at $\sigma_{\mathrm{PSF}} = 0.8°$. The directional uncertainty in the absolute positioning of the ARCA21 detector events is dominated by the knowledge of the absolute orientation of the detector on Earth, as indicated in the analysis for the very-high-energy event KM3-230213A performed by the KM3NeT collaboration [13]. This event was observed with the same detector configuration used in this stacking analysis. Therefore, the approach followed has been to treat this detector systematic in the same way, with an estimated uncertainty of $\sigma_{\mathrm{pointing}} = 1.5°$ for the 68% containment region. Considering these systematic angular uncertainties, the minimum ON radius to be inspected (for the case of a very well localised GRB event) is $\sim 1.7°$, according to equation (2).

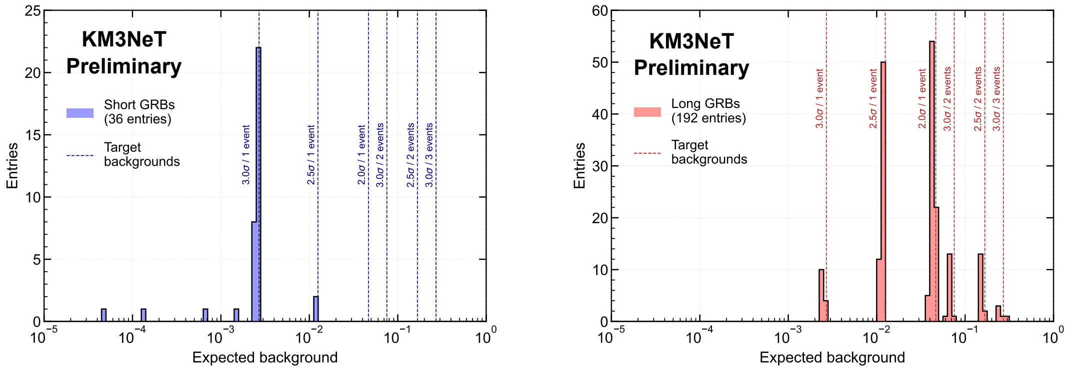
The event selection optimisation is based on the m-σ/n-events approach. Once the geometry of the ON and OFF regions and the time windows are determined, each analysis is optimised to select the events which reduces N^i_{OFF} in each band in such a way that the background n_{BKG} is as low as possible (according to equation 1), while ensuring that the statistical uncertainty in the background is $\leq$ 30%. This corresponds to achieving in each individual analysis a given target background value: $2.70 \cdot 10^{-3}$ (for 3σ/1-event), $1.25 \cdot 10^{-2}$ (for 2.5σ/1-event), etc, depending on the particular ON/OFF geometry. The meaning of the m-σ/n-events quote is that, given the background value, n events found in the ON region after unblinding are enough to claim a pre-trial significance of at least m sigmas for that individual analysis. This optimisation approach is used in the real-time searches being currently conducted by KM3NeT [14].

The key point of the optimisation of the event selection is that different selections are performed in each elevation band, being stricter for regions above the local horizon of KM3NeT, where a larger contamination of atmospheric muons is found. The selection is done on the variable called "likelihood", defined as a quality parameter of the reconstruction of the events. A fixed preselection is also applied to ensure that data events with minimal quality values are used in each individual GRB analysis.

5. Stacking procedure

The presented stacking method is based on a background-rejection procedure. The final result of the analysis is the determination of the significance of the observed data to deviate from the null hypothesis (i.e., data compatible with the expected background). This global significance is determined as a stacking combination of the significance for each individual search, quantified by the pre-trial p-value of each analysed GRB. The analysis has been conducted in a blinded manner, as initially only the OFF region has been inspected in order to determine the expected background for each GRB search. The distribution of these expected backgrounds from the individual searches has been used to characterise the distribution of a given Test Statistic (TS) under the null hypothesis. Finally, after unblinding, the ON region has been inspected, and the compatibility of the observed TS with respect to the null hypothesis has been quantified.

Figures 2a and 2b present the distributions of the expected background in the ON region for the short and long GRB subcases, respectively. As can be seen in Figure 2a, most of the analyses



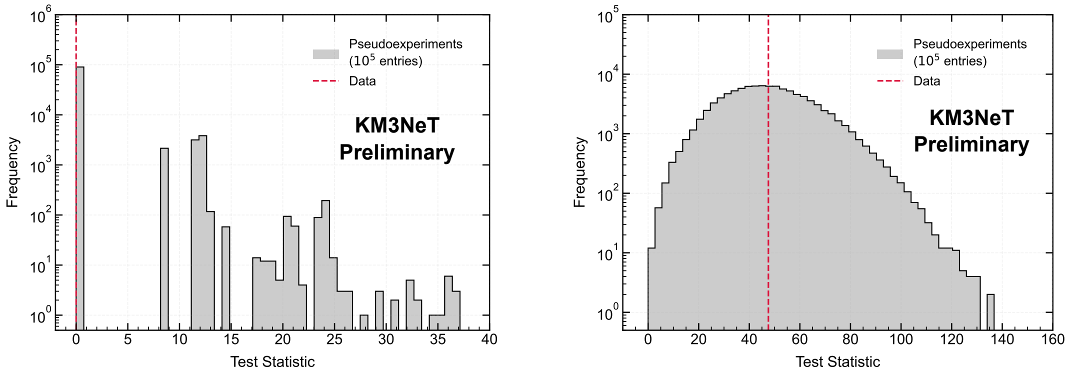
(a) **(b)**

Figure 2: Expected background distributions for the individual analyses of short (left) and long (right) GRBs. The different pre-trial significance levels are indicated as vertical lines.

have been successfully optimised reaching a target background of $3\sigma/1$-event. GRBs with expected backgrounds below 10^{-3} events correspond to the analyses of GRB230116B, GRB230906A and GRB230430A, cases of well-localised GRBs resulting in the smallest possible ON regions according to the detector systematics. In Figure 2b, for long GRBs, most analyses have been optimised for a target background of $2\sigma/1$-event. This behaviour is explained by the RoI radius of these GRB events and the extended signal time window (leading to higher backgrounds as shown in equation 1). The lowest-background case is found to be GRB230506B, a well-localised GRB with expected background $2.3 \cdot 10^{-3}$.

After obtaining the expected background for each individual analysis, a p-value can be assigned independently to each, assuming Poisson statistics, once the number of events in the ON region is determined. The p-value is defined as $p_i = \sum_{k=n^i_{ON}}^{+\infty} \text{Poisson}(\mu_i, k) = 1 - \sum_{k=0}^{n^i_{ON}-1} \text{Poisson}(\mu_i, k)$, where $\text{Poisson}(\mu, k) \equiv \frac{\mu^k e^{-\mu}}{k!}$ is the probability of observing k events in a given time interval with expected value μ. The stacking combination of p-values, used to determine the overall significance of the dataset, is done using the test statistic $\text{TS} = -2\sum_i \log(p_i)$, commonly known as Fisher's formula [15]. In the most general approach, Fisher's method indicates that under the null hypothesis and for independent p-values, the collection of p-values is uniformly distributed and the TS follows a chi-squared distribution with $2n$ degrees of freedom, where n is the number of tests being combined. However, given the relatively low number of GRBs analysed in each population (constrained by the livetime of the detector) and the small expected background required, the analysis is facing a 'physical boundary'. This implies that the significance cannot be computed using the chi-square distribution from Fisher's method, as the p-values are not uniformly distributed. The TS distribution is instead directly constructed using pseudo-experiments drawing from the previously obtained values of the expected background. This TS distribution is later used to evaluate the significance of a deviation in the data with respect to the null hypothesis.

In each pseudo-experiment, background-compatible values of n^i_{ON} for each individual search have been obtained through random Poisson trials, using the expected background population as the expected Poisson values. A total of 10^5 pseudo-experiments have been computed for each case. Figures 3a and 3b present the distributions of the TS for the stacking analysis of short and



(a) Short GRBs **(b)** Long GRBs

Figure 3: Test statistic distributions for the stacking analysis of short and long GRBs. The dashed red line denotes the observed TS.

long GRBs, respectively. The peaked distribution observed for the TS of short GRBs is attributed to the discrete nature of the Poisson distribution, given the low number of short GRBs analysed during the ARCA21 period. For long GRBs, where the phase space of possible outcomes for the pseudo-experiments is larger (and the expected background is also slightly larger), the distribution exhibits a more continuous-like shape.

After unblinding, the actual number of data events inside the ON region has been inspected. The results are summarised in Table 1, which includes the TS determined from the data (see Figure 3) and the significance of the observation in terms of p-value. For the case of short GRBs, no data event have been found in any of the individual GRBs inspected. For long GRBs, 9 out of the 192 inspected GRBs yielded a pre-trial p-value lower than one, a result interpreted as compatible with background fluctuations. The most significant case is GRB230718A, with a pre-trial p-value of 0.034 (2.1σ assuming a 2-sided Gaussian), corresponding to two events in the ON region with an expected background of 0.29 events. The post-trial p-value, found to be background compatible, has been determined by studying the distribution of the most significant p-value in Monte Carlo simulations.

	TS	p-value	Most significant	Expected background	ON events	Pre-trial p-value	Post-trial p-value
SHORT	0.0	1.00	-	-	-	-	-
LONG	47.6	0.48	GRB230718A	0.29	2	0.034	0.68

Table 1: Results of the stacking search, both for the case of short GRBs and long GRBs.

6. Conclusions

In this contribution, a stacking search for neutrinos coming from GRBs observed during the data-taking period of the ARCA21 detector has been presented. The individual analyses are based on a binned ON/OFF approach currently being used by the online searches (i.e., in real-time) of KM3NeT. This is the first time that online-dedicated tools have been used including offline features, i.e., data incorporating refined calibrations and considering systematic effects in the searches. While the individual offline searches have been found to exhibit a slightly improved performance compared to the online searches (as expected, thanks to the larger amount of data events available due to the improved calibrations), the overall online/offline efficiencies have been found to be in reasonable agreement, given the particularities of each dataset.

No significant excess of candidate neutrino events coming from the population of GRBs inspected has been observed. The dataset has been determined to be in agreement with the atmospheric background expectations determined for both long and short GRBs.

The real-time search for cosmic neutrinos in correlation with GRB events continues, with KM3NeT constantly monitoring external GRB triggers. Future stacking analyses are expected to improve these results by incorporating extended datasets from different partial configurations of the ARCA detector and the inclusion of cascade-like events in the searches.

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