Università degli Studi di Genova

Short Thesis.

Neutrino astrophysics with the ANTARES telescope.

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The ANTARES underwater neutrino telescope was successfully build and operating in the Mediterranean Sea. It has a capability to detect charged particles by the Cherenkov light using an array of the 875 photomultipliers. Ultra high energetic muon neutrinos produce muons with almost the same direction and energy as the origin neutrinos so their detection gives information about the astrophysical source. 

The main task for the telescope is the search for the cosmic source of the neutrinos. SNR, AGN, micro quasars are candidates for point like neutrino sources, the Galactic Center, the Galactic Plane, Fermi bubbles are candidates for extended sources.

My PhD thesis consists to determine the minimum neutrino flux emitted by the two large Fermi bubbles structures measurable by the ANTARES telescope on the basis of the data collected from 2008.

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1. Introduction

Neutrinos are the lightest particles known and they can interact only by a weak force. These unique properties allow them to act as unique transmitter of information. In the space they can go through interstellar matter, escape from the dense cores of the sources and go without any deflections even through the strong magnetic fields. So instead of using photons like classical astronomers do, one could try to use neutrinos to look deeper in space, look behind the nebulas, look inside the sources and etc. However these advantages of neutrinos in respect to photons and hadrons bring a problem of their detection. One needs megaton detector mass to try to detect astronomical sources.

But not only the possibility to find more sources is opens when one uses neutrinos in the telescopes. Probably the most interesting result will be in understanding the acceleration of cosmic particles in space. There are several sources detected and there are gammas arriving from them with energies above TeVs. So far there are two conquering hypothesis for the most discovered sources: leptonic model and hadronic. In the leptonic models electrons are accelerating first, in hadronic protons and heavier ions. Gammas can be produced in both acceleration mechanisms (by the electrons via inverse Compton process or by decaying pions from the accelerated protons interacting with the matter surrounding the source). Also decaying pions producing similar quantity of neutrinos but no neutrinos are expected from electrons. So neutrino detection from the source will be a smoking gun for the hadronic model.

Neutrinos produce charged lepton (electron, muon, tau) and hardronic shower during a weakly interaction with matter. If one wants to do a telescope with an angular precision of a degree or less, one needs to use muons that have the longest tracks in the medium (roughly 1 meter per 4 GeV). Muons can be detected by the Cherenkov light emitted in the medium due to the passage of charged particles which velocities are higher then velocity of light in the medium. Muon track is very less deviated from the neutrino one at energies $\gtrsim$ 10 GeV. So, for the neutrino astronomy one normally speaks about neutrino energies of several tens or even hundreds of GeVs. Also neutrino cross-section grows linearly with the energy. Additionally, not only the previously described method can be used for the neutrino detection. At ultra-high energies (above PeVs) one can try to use acoustic and radio waves emitted during the neutrino interaction and hadronic shower propagation through the matter. Two working detectors in the water: ANTARES in the Mediterranean sea and Baikal in the lake with the same name. There is an about 1 km$^3$ project in ice at South Pole (IceCube) and there are two smaller working detectors in the water: ANTARES in the Mediterranean sea and BAIKAL in the lake with the same name.

2. High energy neutrino astrophysics

To start this chapter it is worth to mention a phrase from the J. Bahcall "Neutrino Astrophysics" book: "The title is more of an expression of hope than a description of the books contents....the observational horizon of neutrino astrophysics may grow...perhaps in a time as short as one or two decades." History shows that he was absolutely right especially in the low energy of the neutrinos: the detection of the solar neutrinos and super
nova neutrinos from the SN1986A become a classical part of the university books. There are also strong evidences that the high energy astrophysics is possible and may become true soon. First is that cosmic rays of $E^{20}\text{eV}$ were detected and second is that the high energy gamma ray sources were observed.

2.1. Cosmic rays. The cosmic radiation incident at the top of the terrestrial atmosphere includes all stable charged particles and nuclei with lifetimes of order $10^6$ years or longer. Technically, primary cosmic rays are those particles accelerated at astrophysical sources and secondaries are those particles produced in interaction of the primaries with interstellar gas. Thus electrons, protons and helium, as well as carbon, oxygen, iron, and other nuclei synthesized in stars, are primaries. Nuclei such as lithium, beryllium, and boron (which are not abundant end-products of stellar nucleosynthesis) are secondaries. Antiprotons and positrons are also in large part secondary. Whether a small fraction of these particles may be primary is a question of current interest.

Cosmic ray spectrum measurements with air-shower detectors shown in fig. 1 demonstrates that protons and heavier nucleons with energies in the very broad range extending to $10^{20}\text{eV}$ arrive to the Earth. The above mentioned spectrum contains primary and secondary particles. However only charged particles can be accelerated. The known stable charged particles are protons and electrons. If first of them which can be not only protons, but ions in general are accelerated in a source, then due to interaction with the matter surrounding the source neutrinos and gammas should be created via pion and kaon decays. The presence of the cosmic rays with an assumption that their primary particles were hadrons makes high energy neutrino detection theoretically possible. Instead if electrons are accelerated then only gammas maybe produced via inverse Compton process.

The question where the high energy cosmic rays are accelerated still remains on the interesting unresolved problem in the astroparticle physics. The spectrum of the cosmic rays has a power law decrease with 2 changes on the power spectrum coefficient. At several PeVs it changes from $E^{-2.6}$ to a steeper one. This point was named a knee. It is believed among the most physicists that the most galactic sources accelerate particles till the energies around the knee so the cumulative distribution has this steepening. The next change in the power law spectrum can be explained that the cosmic rays coming below the knee have galactic origin while higher energies can not be gained by the galactic sources so the population of the cosmic rays above the ankle has an extragalactic origin.

For the source accelerating cosmic rays it could be extremely efficient to localize it on the sky by detecting high energy particles and compare the observations with the optical telescopes. Air-shower detector don’t have a good angular resolution due to the fact that the primary charged particles itself are deflected in the magnetic fields (Earth’s and interstellar magnetic fields) so pointing accuracy is not possible for such instruments. Instead recently developed gamma ray detectors revealed several very interesting localized sources of the high energy radiation.
3. Possible sources of the high energy neutrinos from the gamma ray observations

Describe the gamma ray detectors. Sources.

Most of them are supernova remnants surrounded by the molecular clouds (SNR MC). Supernova remnant RX J1713.7-3946 detected by H.E.S.S. has up to 30 TeV gamma rays in its spectrum (fig. 2). The idea of the explaining CR below the knee with shock acceleration mechanisms in SNR becomes very popular last years even if recent fair theoretical calculations or Monte Carlo simulations still can not reach a PeV thresholds of energies.

A presence of the high energy gamma point sources such as previously mentioned RX J1713.7-3946, other SNR MC such as Vela Jr and Vela X, and several other types of the sources such as Cygnus Region which is a star forming region is promising hope for the neutrino detection from them or similar sources and opening an era of the neutrino telescopes astronomy. The ideal case is that only hadrons are accelerated in these objects (pure hadronic model). In this case all the gamma rays are coming together with a similar amount of neutrinos. Their exact quantity may be calculated from the measured gamma ray flux. For the RX J1713.7-3946 the expected number of the events per effective detector...
area is \( I_{\mu+\mu^-} = 2.4 \pm 0.3 \pm 0.5/\text{km}^2 \text{ yr} \) [1]. This shows that size of the detectors should be on order of kilometers.

The center of our galaxy is an area of the active star formation. In this region SN explosion rate is very high which makes it interesting for the neutrino detection. Another possible extended source of the neutrino so-called Fermi bubbles will be explained in the proper section below. Both regions have significant high energy gamma emission.

3.1. GRB.

3.2. Exotic high energy neutrino sources. Talk about dark matter.

4. Neutrino detection

4.1. Neutrino interaction. Neutrinos interact only with a weak force. At high energies the deep inelastic scattering on the hadrons cross sections dominate over other possible interactions. There are two main channels: charged current (CC) via \( W^\pm \) boson and neutral current (NC) via \( Z \) boson. Both are presented in fig. 3. In the first the high energy lepton is produced. The cross section can be estimated by the equation [2]:

\[
\frac{d\sigma}{dx dy}(\nu N \rightarrow l^- X) = \frac{G^2_F}{\pi} [(d(x) + ....) + (1 - y)^2(\bar{u}(x) + ...)]
\]

and for antineutrinos:

\[
\frac{d\sigma}{dx dy}(\bar{\nu} N \rightarrow l^+ X) = \frac{G^2_F}{\pi} [(\bar{d}(x) + ....) + (1 - y)^2(u(x) + ...)]
\]
Figure 3. Neutral current interactions (left) in which neutrinos transfers and energy to hadron creating a cascade, charged current interactions (right) in which high energy lepton is created together with a hadronic cascade.

Figure 4. Neutrino (left) and anti-neutrino (right) mean inelasticities $\langle y \rangle = \langle 1 - E' / E \rangle$ [5].

where $x = Q^2 / (2M\nu)$ is a fraction of the nucleon’s energy carrying by quark, $\nu = E - E'$ is the energy lost by the lepton in the nucleon rest frame and $1 - y = E' / E$. As it can be seen the cross section grows rapidly with the decrease of $E - E'$ and increase of $E' / E$ so when the charged lepton brings out the incident neutrino energy. Including the momentum conservation law this means that the lepton has similar energy and the direction of the neutrino. The angle and energy change taken from the simulations described below are presented in fig. 4 and 5.

Muons due to their bigger mass in respect to the electron and longer life time in respect to the tau have the longest tracks in the medium. Their energy losses in the high energy region are proportional to their energy and starts at about 2MeV/cm at 1 GeV in water (see fig. 6). Muons with TeV energies can pass through kilometers of water (fig. 8). Their passage causes Cherenkov light, $e^+e^-$ pair production, Bremmstrahlung radiation and photonuclear interactions. The emitted light can be collected by the array of the photomultipliers (PMTs) and the track reconstructed by the light time arrival.
Figure 5. Medians of the distributions of muon directions at the can for the atmospheric and an $E^{-2}$ neutrino flux [5].

Hadron products of the interaction create hadronic shower. Its size however is rather small in respect to the muon track which makes it difficult to detect with a sparse array of the PMTs. High energy electrons instead instead of muons have a very high probability to radiate bremsstrahlung photons after a few centimeters of water. This immediately creates an electromagnetic shower due to the $\gamma \to e^+e^-$ pair production. For the 10 TeV electron, the shower length is only about 10 meters. For the tau due to its short life time it is possible in principle to see double shower structure with a first shower coming from the interaction point of the incident neutrino and a second one due to the tau decay which should be separated by the tau decay length $l_\tau = \gamma c t_\tau \approx 50(E_\tau/\text{PeV})\text{m}$.

Also it is possible in principle to detect a sound which is created by the expanding shock wave of the heated medium due to the neutrino interaction. This method seems to be very promising for energies above $10^{20}\text{eV}$.

So far for the energy range of $100\text{GeV} - 1\text{EeV}$ the detection of the muons by the Cherenkov radiation is the most precise and efficient method for the neutrino telescopes.

4.2. **Cherenkov radiation.** When a charged particle travels through a medium it polarizes the atoms around its trajectory. These electric dipoles are symmetrically oriented around the track when the particle is moving with a speed $u$ smaller than the speed of light.
c/n in the medium, where n is the index of refraction of the medium under consideration. If \( v \leq c/n \) this symmetry is broken and dipole radiation is emitted, known as Cherenkov radiation. Cherenkov light is emitted at a fixed angle, creating a cone of light around the particles' track, and this fact makes it useful for reconstruction purposes. The Cherenkov angle can be calculated with the help of Fig. ?? as follows. Consider a charged particle traveling with velocity \( u \) in \( c/n \) emitting spherical waves of light along its trajectory. A spherical wave emitted at point A will reach point C at the same time as the charged particle arrives at point D. The cosine of the angle \( \theta_c \) is given by:

\[
\cos \theta_c = \frac{AC}{AD} = \frac{tc/n}{t\beta c} = \frac{1}{\beta n}
\]
where for relativistic particles ($\beta \approx 1$) and water as the propagation medium ($n = 1.33$) the value of this angle is about $41.2^\circ$. The spherical waves emitted at every point on the trajectory collectively create a wavefront in the shape of a cone. The number of Cherenkov photons emitted per unit track length $x$ and wavelength $\lambda$ is:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi \alpha Z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right)$$
where $Z$ is the charge of the particle and $\alpha$ the electromagnetic coupling constant. In the optical part of the spectrum (350 nm – 600 nm) which is of interest to us, this amounts to almost 200 emitted photons per cm. As the muon propagates through the medium, the Cerenkov light it produces is affected by absorption and scattering. The absorption is characterized by the absorption length $\lambda_{abs}$, which is the average distance at which a fraction of ($1/e$) of the photons is absorbed. Correspondingly, scattering is characterized by the scattering length $\lambda_s$ in the same way.

5. Atmospheric Background

Cosmic rays interacting with an atmosphere produce hadronic showers containing mesons. Charged pions decay mostly to muons and neutrinos. Also there is a contribution from kaons and other processes to the atmospheric muon and neutrino background. Rate of the muons from the overburden distance in rock is shown in fig. 9. Basically one can decrease the muon background by 2 orders of magnitude going 2 km underwater. However even at this depths the background is orders of magnitude bigger than the expected cosmic neutrino signal. The Earth is not transparent to the muons so it is possible to use it as a shield looking for up-going signal from neutrinos. For the atmospheric neutrinos the rate almost independent for up-going and down-going events with a difference coming only due to the geomagnetic effect which changes flux of the cosmic rays. The flux of the atmospheric neutrinos is also orders of magnitude bigger than the expected signal from the cosmic sources however it decreases with the energy.
Figure 10. Depth contour plot near the ANTARES site.

6. THE ANTARES DETECTOR

The ANTARES\textsuperscript{1} detector is a pilot project to demonstrate a possibility of the neutrino telescope creation and stable operation during the years in the sea water on the big depth. The ANTARES detector is located near Toulon, France. The coordinates are $42^\circ50'\text{N}$ and $6^\circ10'\text{E}$. Its location makes it sensitive to a large part of the southern sky, including the galactic center region. The detector is located at a depth of 2475m on the bottom of the Mediterranean sea. The seabed in this place is quite flat (fig. ??) which is promising for the further project extension.

6.1. General overview. The ANTARES detector consists of 12 vertical strings, each one holding photomultiplier (PM) tubes for Cherenkov light detection. ANTARES comprises 885 detector units, called optical modules (OM). The OM is a sphere containing the PM tube. A single storey consists of three such optical modules mounted on the optical module frames (OMF). Five storeys complete a single ANTARES sector. The optical modules point downwards at a 45\textdegree\ angle with respect to the vertical. The OMF is a mechanical structure which, in addition to the OMs, supports a titanium container holding the local control module (LCM) and housing offshore electronics and processors. Five storeys together constitute a sector which is an individual unit in terms of power and data transmission. A line is a chain of 25 OMFs, i.e. 5 sectors, linked by an electro mechanical cable (EMC). The distance from storey-to-storey is 14.5 m and the first storey of each line is located 100 m from the bottom of the sea. The reason for this is to leave enough space to allow for the

\textsuperscript{1}Astronomy with a Neutrino Telescope and Abyss environmental RESearch
development of the Cherenkov cone from up-going particles. The inter-line spacing varies between 65-70 m.

Each line is anchored to the bottom of the sea with the bottom string socket (BSS) and a dead weight, and is held vertical by a buoy at the top. Every BSS contains a string control module (SCM), a string power module (SPM), calibration instruments and an acoustic release system. The acoustic release system allows for the recovery of the complete line. The SPM houses the power supplies for all sectors in a line while the SCM contains electronics for slow control. The full configuration is octagonal as seen in figure 2.9. In each sector, one LCM is the master LCM (MLCM) and its role is to handle data distribution between all LCMs in the sector. A Dense Wavelength Division Multiplexer (DWDM) multiplexes the data signal from the 5 sectors onto one pair of optical fibers. Data and power are transmitted between the lines and the shore via the 40 km long main electro-optical cable (MEOC) connected to the junction box (JB), and interconnecting link cables (ILC). Data arrives onshore in a PC farm located at the shore station (La Seyne sur Mer) where the ANTARES control room is located and data filtering is applied. Filtered data are copied and stored remotely at a computer center in Lyon once a day. The instrumentation line (IL07) contains oceanographic sensors for measurements of environmental parameters. Line 12 and IL07 contain hydrophones which are used to test the feasibility of acoustic neutrino detection. The IL07 and the top sector of Line 12 do not contain OMs.

Each OM consists of a pressure resistant glass sphere, 43 cm in diameter and 15 mm thickness. It contains a Hamamatsu R7081-20 hemispherical PM tube [Hama] with a diameter of 25cm and an effective sensitive area of 440cm². Each PM tube has 14 amplification stages and a nominal gain of $5 \times 10^7$ at a high voltage of 1800 V.

The wavelength sensitivity range of the PM tubes is 300-600nm. The peak quantum efficiency (QE) is 23% at light wavelength of 350-450 nm. The charge resolution and transit time spread (TTS) of the PM tubes are 40% and 1.5 ns respectively. The dark count rate at the 0.25 photoelectron level is about 2 kHz. Each PM tube is surrounded by a metal cage to minimize the influence of the magnetic field of the Earth on its response. The high voltage is provided by an electronics board mounted on each PM tubes socket. Each OM also contains an LED calibration system explained in more detail in section 2.8. The PM tube is glued to the outer glass sphere by means of a transparent silicon rubber gel. The glass hemisphere behind the PMT is painted black and contains a penetrator which provides the power and data transmission connection to the outside.

6.2. **Optical water properties.** The performance of the detector depends on the optical properties of sea water, since light propagation in a medium is affected by absorption and scattering. Absorption reduces the amount of light that reaches the OMs while scattering affects the path of the photons and their arrival time on the OMs. Absorption and scattering reduce the intensity of light as, $I(x, \lambda) = I_0(\lambda)e^{-\frac{x}{\lambda_{abs}(\lambda)}}e^{-\frac{x}{\lambda_{s}(\lambda)}}$, (2.5.1) where $x$ is the optical path travelled by light and $\lambda_{abs}$ and $\lambda_{s}$ the absorption and scattering lengths, respectively. The absorption length as a function of the photon wavelength is shown in figure 2.10. Figure 2.11 illustrates the wavelength dependence of the scattering length.
6.3. Optical background. There are two background contributions to photon detection in sea water. The first one is the decay of the radioactive potassium isotope 40K,

\[ 40K \rightarrow 40Ca + e^- + ?\nu e \ (BR = 80.3\%), \ (2.5.2) \]
\[ 40K + e^- \rightarrow 40Ar + ?\nu e + ?\nu \ (BR = 10.7\%). \ (2.5.3) \]

The emitted electron energy in (2.5.2) can take values up to 1.33 MeV. A large fraction of these electrons is above the Cerenkov threshold for light production. The photons emitted in the electron capture process (2.5.3) have an energy of 1460 keV. These photons can lead to Compton scattering producing electrons above the Cerenkov threshold. The second optical background contribution comes from luminescence produced by various organisms (bioluminescence). Bioluminescence can give rise to optical background up to several orders of magnitude above the 40K contribution and these bursts can last for seconds. In figure 2.12 the typical counting rate on a PM tube, i.e. hit frequency, as a function of time is illustrated.

The fraction of time during which the instantaneous background rate exceeds the baseline rate by at least 20% is called burst fraction. After monitoring deep sea currents, it was found that the baseline component is correlated neither with the sea current nor with the burst frequency. However, long-term variations of the baseline were observed. A strong correlation between bioluminescence and sea current velocity has been observed, as shown in figure 2.13.

6.4. PMT study. Since the track reconstruction is based on the light arrival to the PMT it is necessary to know its TTS precisely to be used in the detector simulations later. The performed measurements are shown in fig. 12. The measure was performed with uniform illumination and with a point like beam toward the center of the photocathode. In both a significant tail toward increasing arrival times can be observerd. According to [7], the tail, a bit larger for uniform illumination, might be ascribed to an additional inelastic scattering of the photoelectron in the first dynode while the structure at 50 ns from the main peak is produced by the elastic scattering. To this extent, assuming an uniform electric field of 60 V/cm in the 14 cm distance of the first dynode from the photocathode, the 50 ns of the peak roughly corresponds to the round trip of one electron from the first dynode to the
Figure 12. Dotted curve: point like illumination, continuous: uniform illumination;

photocathode and its way back. On the left side from the peak, the pre-pulses contribution may be seen in the 10-15 ns preceding the main pulse. As expected, the contribution is more sensitive for the point like illumination which is directed toward the first dynode. In the same plot the dashed curve represents the Gaussian fit of the left side of the main peak. In the regular process the photon is converted to the electron and electron is multiplicated on the dynode stack. Additionally several different situations may happen (fig. 13):

1. After-pulses type 1: they appear in the first 80 ns after the main pulse and can be produced by the luminous reaction on the dynodes while bombarded by the electrons (fig 1b) or by the electrons escaped from the dynode in the direction to the photocathode.

2. After-pulses type 2: appear in the 80 ns -16 µs interval after the main pulse due to the ionization of the phototube gas by the photoelectron. Different ions give different contributions to the after-pulses time distribution (H⁺, He⁺ and heavy ions CH⁺₄, O⁺, N₂⁺, O₂⁺, Ar⁺ and CO₂⁺).
Figure 13. After(1a,1b,2) and late(3,4) pulses origin on a PMT.

(3) Late-pulses: the primary photoelectron suffers elastic or inelastic scattering in the first dynode without a secondary electrons emission, it turns towards the photocathode making a loop and only after it creates a cascade of electrons in the dynodes. The arrival time of the hit will be delayed.

(4) Pre-pulses: They appear due to the direct photoelectron emission on the dynodes from the photons which passed the photocathode without interaction. Due to this, the main pulse is arriving earlier and with smaller charge.

In fig. 14 afterpulses measurements are presented. One can see hits arriving after the main hit shortly after (in 10-40ns) or later (6-8µs). The total contributions of these afterpulses 1.0% and 0.8% correspondingly. The late afterpulses (type 2) doesn’t affect the track reconstructions but simply increase the light background. Instead the fast afterpulses should be considered in the tests of the reconstruction algorithms.

7. Data acquisition

The role of the data acquisition (DAQ) system of ANTARES [Agui 07] is to convert the analogue signal recorded by the PM tubes into a digital format that can be used for physics analyses. This includes preparing the detector for data taking, converting the analog PM tube signal and transporting, filtering and storing the data. In addition, the run settings are archived. The DAQ system is a large network of processors, both on-shore and off-shore. The off-shore processors, integrated in custom made electronics, are connected to the on-shore processors (standard PCs) by the electro-optical cable on the sea-bed. A schematic view of the data acquisition system is shown in figure 2.15.

7.1. Signal digitization. A photon hitting the photo-cathode of a PM tube can produce an electrical signal on the anode. The probability of an electron emission induced by a photon is given by the quantum efficiency (QE) of the PM tube and is a function of the incident photon wavelength. The wavelength dependence of the quantum efficiency is shown in figure 2.16. If the signal amplitude exceeds a certain voltage threshold, the signal is read-out
Figure 14. Time vs amplitude distribution of after-pulses type 1a&1b (top) or type 2 (bottom).
and digitized by a custom application-specific integrated circuit, the Analogue Ring Sampler (ARS) [Fein 03]. The threshold is typically set to 0.3 photoelectrons to suppress the PM tubes dark current although this can vary among different PM tubes. The ARS can distinguish between single photoelectron pulses (SPE) and more complex waveforms. 

Four additional autonomous transponders are located around The criteria used to discriminate the two classes are based on the amplitude of the the detector to increase the accuracy of the global alignment. The depth of the BSS is determined with pressure sensors located at the BSS and during connec- gate. Onlytiocnhatorgtheeajundctiionmeboinxf-woritmhatpiorenssiusrreescoensdoredonfothreSsPubEmeavrienet.sT.henscpaeseedsooflangeor signal, the time above threshold or the occurrence of multiple peaks within the time double pulses, the ARS can sample the PM tubes signal continuously with a tunable sampling frequency of 150MHz up to 1GHz holding the analog information on 128 26 switched capacitors. For physics data taking only SPE hits are used. A local clock is used by the ARS chips for the determination of the arrival time of the hit. The time resolution of the system is better than 0.4ns. The charge of the analog signal is integrated and digitized by the ARS over a certain period of time using two 8-bit ADCs. The integration gate is typically set to 40ns. After this period, the ARSs exhibit a dead time of around 200ns. Each PM tube is read by 2 ARSs operating in a token-ring scheme to minimize the effect of the dead time. The combined charge and time information is called a level 0 (L0) hit. All0.625ARS chips in an LCM are read out by a Field Programmable Gate Array (FPGA) that arranges the hits produced 0.2 in a time window into a dataframe and stores it in a 64MB Synchronous Dynamic Random Access Memory (SDRAM). The complete set of dataframes from all ARSs 0.15 that correspond to the same time window is called a TimeSlice. A 20 MHz clock is used to provide a common time for all ARSs. It is synchr0o.1nized to the GPS time with an accuracy of 100 ?s. Through the optical fiber network, all local clocks on the different storeys are synchronized with the master clock.

7.2. Data transmission. Each offshore CPU runs two programs controlling the data transmission. DaqHar- ness handles the transfer of dataframes from the SDRAM to the control room, while SCHarness handles the transfer of calibration and monitoring data (slow-control data). Transmission Control Protocol and Internet Protocol (TCP/IP) is used for communi- cation between the CPUs and for data transport. The LCMs in a sector are connected to the MLCM in the same sector using an optical bidirectional 100 Mb/s link. These links are merged using the Ethernet switch of the MLCM into a single Gb/s Ethernet link. Each string is connected with an electro-optical cable to the junction box which in turn is connected to the shore station with the 40 km long electro-optical cable. The data are transported using dense wavelength division multiplexing technique (DWDM) [Seni 92]. Each sector and each string use a unique pair of wavelengths to transmit data along a single optical fibre to shore. The ControlHost package [Guri 95] is used for data transfer and communication among the processes in the DAQ system.

7.3. Data filtering and storage. All data, after the off-shore digitization, are trans- ported to shore without any further selection. The total data output of the detector in periods of low bioluminescence (60-90KHz per PMT) is 0.3-0.5GB/s. Since most of it is
optical background it has to be filtered appropriately. Trigger algorithms are applied to identify signals from particles traversing the detector by searching for space-time correlations in the data. Such physics events selected by the DataFilter program, are subsequently written to disk with the program DataWriter. The DataFilter looks for a set of correlated hits in the full detector in a window of about 4 sec. If an event is found, all hits during this time window are stored. If ANTARES receives external GRB alerts all detector activity is recorded for a few minutes. Data filtering or triggering is examined in more detail in the following section.

7.4. **Trigger.** Physics data taking runs in ANTARES last for about three hours. The average data rate of 625 MB/s for each detector string is reduced after filtering to \( \approx 0.15 \) MB/s for the whole detector. The duration of the run along with the start and end times, as well as the trigger conditions are stored in the database. The majority of the data is optical background due to potassium decays or bioluminescence. This overwhelming background can be reduced by a factor of 104 on the first filtering (triggering) stage [Jong 05a]. Such a reduction is achieved by searching for hits within 20 ns in different PM tubes of the same storey or single hits with an amplitude higher than 3 photo-electrons. Hits satisfying these criteria are called L1 hits. All other hits are called L0. This kind of selection is based on the assumption that background hits should be uncorrelated and signal hits correlated. Two recorded hits on two different PM tubes are considered causally related if they satisfy,

\[ -t - ng \cdot d, (2.7.1) \]

where \( t \) is the time difference between hits, \( d \) is the distance between the PM tubes and \( ng/c \) is the group velocity of light in water. In this time window an additional 20 ns is included to allow for uncertainties in the hit positions, time and light scattering. Hits satisfying this condition constitute a cluster. If this cluster is large enough (typically 5 L1 hits) it is stored as a physics event. Physics events contain L1 hits that fired the trigger as well as all L0 hits in 2.2 s from the first and last L1 hit. The reason for this is that this is the time it takes for a relativistic muon to travel approximately 650 m i.e. traverse the detector. The hits contained in a physics event are illustrated in figure 2.17. In addition to this first level selection, a second trigger level (e.g. 3N trigger) can be applied. This includes a scan over a certain number of directions searching for coincidences compatible with the Cerenkov light emission hypothesis. The expected time of a Cerenkov photon is:

\[ t = r1 + t0 + c z1 \tan \theta + u \sin \theta, (2.7.2) \]

\( CgC \) where \( t0 \) is simply an initial reference time on the muon track. The first term in equation (2.7.2) describes the distance along the track up to the point where the Cerenkov photon was emitted and the second term is the path from the point of photon emission to the PM tube. This is illustrated in figure 2.18 for two illuminated PM tubes, where \( ti = (t1, t2) \), \( zi = (z1, z2) \) and \( ri = (r1, r2) \). Two hits are considered compatible with the Cerenkov hypothesis if:

\[ -t2-t1 - z2-z1 +R \tan \theta C + 20ns, (2.7.3) \]

where we used the assumption that \( \cos \theta C = 1/ng \). The 20 ns are added to account for uncertainties on the time calibration, light scattering, and position of the storey. Additional clusters can be formed by L1 hits. An example of this is the T3 trigger [Carr 07]. It accepts
more background hits, increasing the sensitivity in the low energy region with the drawback of triggering on additional events that will be reconstructed badly i.e. it exhibits a higher efficiency at the expense of lower purity. A T3 cluster is defined as at least 2 L1 hits in 3 consecutive storeys within a time window of 100 ns for adjacent and 200 ns for next to adjacent storeys.

8. Detector calibration

The precision of track and energy reconstruction is strongly dependent on the precision of time, position and charge measurements. In this section, the calibration systems used in ANTARES are discussed.

8.1. Time calibration. The time calibration in ANTARES [Agui 11] is performed using pulses from LED and laser devices. A timing resolution on the recorded PM tube signals of 1 ns is required to ensure the reliability of track and energy reconstruction. The internal clock calibration system measures the time offsets of each storey. It consists of the master clock on-shore and a bi-directional optical communication system connected to all LCMs. The relative offset of each local clock can be measured by using a calibration signal sent by the master clock and echoed back. The clock system assigns an absolute event time with a GPS master clock synchronization accuracy of 100 ?s. The optical beacon system [ANTA 07] is used to calibrate the relative offsets between the PM tubes. Four blue (472 nm) LED beacons on storeys 2,9,15 and 21 of each detector line and two green (592nm) laser beacons on the BSS of L7 and L8 are used for this purpose. The LED beacons are used for intra-line calibration purposes while the laser beacon, being much more powerful and able to illuminate all the lines, is used for inter-line calibration. An initial set of time offsets is determined in the laboratory prior to deployment. After deployment, these values may change due to different factors such as temperature changes or stresses in the cables. Using the optical beacon system they are monitored periodically and readjusted as necessary. A second calibration system consisting of a blue (470 nm) LED inside each OM is used to measure time offsets between the PM tube photo-cathode and the read-out electronics. Internal LED and optical beacon measurements reveal less than 0.5 ns contribution of the electronics to the photon arrival time resolution. Thus, time resolution is dominated by the transit time spread of the PM tubes which is about 1.5ns, and light scattering and chromatic dispersion, which depends on the distance travelled by the photon. The calibration system just described provides a relative time calibration of better than 1 ns.

8.2. Charge calibration. The integrated charge of the PM tube signal has to be converted into the number of photoelectrons that created this pulse. The relation between the signal amplitude and the number of photoelectrons is given by the transfer function of the Amplitude-to-Voltage Converter (AVC). This function is important for the measurement of the amplitude in the PM tube pulse, as well as for the correction of the time slewing of the PM tube signal i.e. the influence of the pulse amplitude and the pulse rise time on the threshold-crossing time, illustrated in figure 2.19. The first step in charge calibration is performed on the test bench where the AVC transfer function is determined. In order
to do this, a pulse generator sends a direct signal to a pair of ARSs operating in a token-
ring scheme. The pulse has a triangular shape with 4ns rise time and 14ns fall time. The
transfer function and the dynamic range of the ADCs exhibit a linear behavior and can
be parametrized by the slope and intercept of the function. In addition to the test bench
calibration, regular in situ calibration runs have to be performed. These runs are used
to determine the pedestal value of the AVC channel, namely the offset AV C0pe value
corresponding to zero photoelectrons, and the single photoelectron peak which is studied
by looking at minimum bias events, since light from potassium decays and bioluminescence
produce in their majority single photons on the photocathode level. The charge spectrum,
ignoring contributions from the second and higher photoelectron peaks, can be described
as [Jong 05b]:
\[ f(x) = A e^{\theta x} + B e^{-\frac{x}{2}}, \]
where the first term corresponds to the contribution of the dark current. The second
term describes the single photoelectron peak as a gaussian with mean $x_1$ and stan-
dard deviation $\theta$. The effects of the dynamic nonlinearity (DNL) of the AVC can be minimized
by considering the integral of the AVC spectrum:
\[ \int x A B \int_0^{x_1} f(x) dx = e^{-\alpha(x-x_0)} + \theta/2, \]
where $\gamma$ is the incomplete gamma function. A fit on the integrated spectrum leads to the
determination of the single photoelectron peak. The same procedure is applied to identify
the pedestal region as shown in figure 2.20. The parametrization used is:
\[ 20 C \int_0^{x_1} (x-x_0)^2 C \int_0^{x_1} + \theta/2. \]

Charge measurements in AVC channels appear to be affected by time measurements
in the TVC channel. This is known as the cross-talk effect and can be attributed to a
cross-talk of the capacitors inside the ARS pipeline. Plotting AVC against TVC values,
as shown in figure 2.21, makes it possible to determine the correction to be applied. After
applying this correction most of the hits in a minimum bias event have a charge of one
photoelectron.

Due to the spread of the PM tube gain, the photoelectron peak is described by a gaussi-
annian function with mean AVC1pe. If the parameters of the gaussian distribution for one
photoelectron are $\alpha_1$ and $\alpha_1$, then for the coincidence of N photoelectrons the parameters of
the gaussian distribution are, where AV C is the corrected AVC value taking into account
the cross-talk effect. Light from potassium decay is also used to monitor how the detector
response evolves with time. A gain drop of the PM tubes is observed and is attributed to
the aging of the phototube. The charge pedestal value is almost constant in time, while
the photoelectron peak drops by around 0.02 photoelectrons per month as can be seen in
figure 2.22. The systematic error on charge calibration is estimated at around 30%[Fehr 10;
Bare 09].

8.3. Position calibration. Due to the flexible nature of the lines, water currents can
displace the position of the optical modules, especially on top storeys. As with timing
and charge information, knowledge of the position of the optical modules is of high impor-
tance for a precise event reconstruction. For this purpose a High Frequency Long Baseline
(HFLBL) acoustic system is used to monitor the positions of five hydrophones along each
The horizontal displacement of the hydrophones on Line 11 with respect to the BSS (0,0) for a period of six months. The East-West tendency of the Line heading is due to the Ligurian current at the detector site. The top storeys of the line experience larger amounts of displacement due to the water current. Image taken from [Brow 09].

The hydrophones are mounted on storeys 1, 8, 14, 20 and 25. A transmitter-receiver is installed at the anchor of each line and some additional autonomous transponders are used. The emitters send high frequency acoustic signals in the 40-60 kHz range and the distances are obtained by measurements of the travel times of the acoustic waves. The distances are used to triangulate the position of each receiver with respect to the emitters on the sea floor. Furthermore, a system of compasses and tiltmeters is used to measure the orientation and inclination of each storey. The shape of each line is reconstructed by performing a global χ²-fit based on a model of the mechanical behavior of the line under the influence of the sea currents. The relative positions of each OM are calculated from this fit using the known geometry of each storey. In order to determine these positions as accurately as possible, knowledge of the water current flow and the sound velocity in sea water is used. These are measured using acoustic doppler current profilers (ADCP) for the water current flow, conductivity-temperature-depth (CTD) sensors to monitor the temperature and salinity of the water and sound velocimeters to monitor the sound velocity in sea water. The relative positions of all the optical modules is monitored with an accuracy better than 20 cm [Ardi 09]. The horizontal movement of a line with respect to the BSS position is illustrated in fig. ??.. The absolute positioning of each anchored detector component is calculated with an accuracy of about 1 m by acoustic triangulation from a surface ship equipped with differential GPS.
The Fermi-LAT experiment has revealed two large spherical structures centered in our Galactic Centre and perpendicular to the galactic plane, the so called Fermi-Bubbles. These structures are characterized by gamma emission with an hard and uniform spectrum (fig. 16) and a relatively constant intensity all over the space.

From the fig. 16, it is clearly seen that gamma flux is compatible with the flat $E^{-2}$ distribution at level of $3 \times 10^{-7} E^2 GeV cm^{-2} s^{-1} sr^{-1}$. This spectrum can be hardly explained by the Inverse Compton process of the highly relativistic cosmic ray electrons requiring...
very specific acceleration features. In other hand a population of relic cosmic ray protons and heavier ions would naturally explain all the features of the Fermi bubbles structure [4].

In this scenario, the presence of high energetic hadrons makes the Fermi bubbles a promising neutrino source for the ANTARES detector. The ANTARES detector, located in the northern hemisphere, has an excellent visibility of the Galactic Center and therefore of the Fermi bubble. So the advantage of this experiment in respect to IceCube, located in the South Pole, is that the visibility of the Fermi-Bubble is almost 100% (see fig. 17).

In this analysis the shape of the Fermi bubbles has been approximated as shown in fig. 18.
Figure 19. Predicted number of neutrino events as a function of the neutrino energy in the case of atmospheric neutrinos and neutrinos from the Fermi-Bubbles for different energy cutoffs. Number of the events is in arbitrary units (which correspond to about 4 years of data with precut described below).

14.1. Energy Spectrum and Cutoff. For the known gamma ray emission with an almost flat $E^{-2}$ distribution it is easy to estimate a neutrino flux assuming pure hadronic model. According to [?] (formula 34 + fig.3 at $\Gamma = 2$) there is the following relation between the neutrino flux and the gamma flux in this case:

\begin{equation}
\Phi_\nu \approx \frac{1}{2.5} \Phi_\gamma
\end{equation}

So, according to fig. 16:

\begin{equation}
E^2 d\Phi_\nu / dE \approx 1.2 \times 10^{-7} E^2 GeV cm^{-2} s^{-1} sr^{-1}
\end{equation}

The energy cutoff may be obtained from the proton cutoff:

\begin{equation}
X_\nu \approx X_p / 20
\end{equation}

Suggested cutoffs from [4] are from 1PeV till 10PeV in the most promising case which will correspond to cutoffs in neutrino spectrum from 50TeV to 500TeV correspondingly. Fig. 19 shows the comparison between the predicted number of detected neutrino events in the ANTARES detector in case of the atmospheric neutrino flux (Bartol flux) and the Fermi bubbles flux considering different energy cutoffs.
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**Figure 20.** Ratio of the events with $\lambda > -6.5$ in one data run to MC vs time of the run start with the exponential fit. Red dots correspond to the selection $|\log_2(\text{ratio/fit})| < 3\sigma$.

### 14.2. Data set selection

For all the analysis following data and MC productions were used:

- Data production: 2012-04 converted to AntDST v3r3 by Fabian
- MC muons v2 RBR by Colas for muons
- MC neutrinos v2.2 RBR by Katya and Luigi (genhen bug fixed)

First selection of the runs was done with following criteria:

- QB $\geq 1$
- no words ”SCAN”, ”PRELIM”, or ”prelim” (we still don’t have an analysis to give this runs back to normal)
- no words ”half” & ”over” - to exclude gain/2, gain/4, gain/8 (this runs are quite different and should be analyzed separately
- the known sparking runs were excluded from the following analysis (see Appendix A)

For the selected runs ratio of number of events in data to MC muons selecting triggers 3N, T3, T2 and TQ which are reconstructed with Aafit with $\lambda > -6.5$ is presented in fig. ?? together with exponential fit. From the fit it seems that the ratio data/MC is decreasing over time. There is about 6% efficiency loss a year with unknown reason which may be an OM detection efficiency degradation (biofouling, PMT efficiency loss due to the photocathode degradation o etc).

For the following analysis it was decided to remove the runs whose ratio of data/MC stays away from the fit. Basically the $|\log_2(\text{ratio/fit})|$ for each run was calculated. The distribution was fitted then with a Gaussian as present in fig. 22. It was decided to keep runs with $|\log_2(\text{ratio/fit})| < 3\sigma$.

At the end 8193 runs were selected starting from March 2008 till December 2011. Also for these runs grouped by 4 calendar weeks a ratio of number of neutrinos (up-going events)
Figure 21. Ratio of the events with $\lambda > -6.5$ in one data run to MC distribution.

Figure 22. Ratio data/MC of the up-going events with $\lambda > -5.1$ in off-zones grouped by 4 calendar weeks.

in data to MC in off-zones with $\lambda > -5.1$ was calculated (the choice of the cut and off-zones selection will be explained later). Similar decrease may be seen in the ratio in fig. ?? although the fit values are consistent with no decrease hypothesis on $2\sigma$ level.

14.3. Off-zones for background estimation. As it is seen from the fig. 19 the presence of the background of the atmospheric muons makes the signal search a difficult issue. The correct background treatment is vital for this analysis.
Figure 23. Visibility of the ANTARES detector in Galactic coordinates. Fermi bubbles area is seen in the center together with 3 off zones around the maximum of the visibility.

The uncertainty on the fluxes of the atmospheric neutrinos during the last years remains more than 20% due to the lack of new measurements of the cosmic ray fluxes and interactions of them with the light atoms in the atmosphere. This and other imperfections of the simulations makes inefficient data/MC comparison for revealing a possible signal. Instead, the so-called off-zone method which is based on the background estimation from the data exists and seems to be promising in this case. The main idea of this method is to compare signal measured in the Fermi bubbles area (on-zone) with a background estimated from the data itself in the area chosen outside (off-zone). The estimated background in both zones (on-zone and off-zone) should have the same properties.

The proposed off-zone was selected in a way that it has the same size and shape as the on-zone and it follows it in the local coordinates of the detector with some fixed delay in time. This allows to have the same expected number of background events, as their number is proportional to the efficiency of the detector, which is a function of the local coordinates only, and it slightly varies in time. The advantage is also that in this case the off-zone is fixed in the sky. Also one can select at maximum 3 off-zones, which reduces the background uncertainty. The Fermi bubbles area and 3 off-zones are showed in fig. 23 together with a visibility of the detector. One can see that visibility of the on-zone and the 3 off-zones is the same.

For the preliminary analysis it has been agreed with the referees (M. Spurio and C. Riviere) that all data taking period can be used freely to optimize cuts and to do data/MC comparison with the restriction to look only at the events coming from the off-zones.
14.4. Validation of the off-zones choice and systematic error estimation. The consistency of the number of events was checked with the following method. Arbitrary cut on lambda and energy from ANN energy estimator was chosen and number of events in 3 zones calculated. As a first test MC neutrinos were used (the final cut removes almost all muons as it will be shown later). For each possible cuts combination in $\lambda$ and energy ($\lambda > (-6...-4.9)$ and $E > (10^2...10^6)$[GeV]) a following ratio of events in the zones was calculated:

\[
R = \frac{|N_{\text{on-zone}} - <N_{\text{off-zone}}>|}{<N_{\text{off-zone}}} \times 100\%
\]  

where $N_{\text{on-zone}}$ is the number of events in on-zones and $<N_{\text{off-zone}}>$ is the average of events in off-zones. This ratio was plotted versus number of events $<N_{\text{off-zone}}>$ in fig. 24. The difference between the ratio and corresponding statistical error indicates the systematic error which can be estimated on order of 1% from the plot.
Figure 25. Difference between number of data events in off-zone 1 and off-zone 2 (black) divided by mean number of events in 3 off-zones as a function of the mean number of events. The same distributions are presented for off-zones 2 and 3 (red), off-zones 3 and 1 (blue). A gray band shows mean statistical error.

Also to do a check with a real data a similar plot for off-zones only is done. In this case there are three different ratios:

\[ R = \frac{|N_{off-zones}^i - N_{off-zones}^j|}{<N_{off-zones}>} \times 100\%, \ i \neq j, \ i, j = 1..3 \]

As in this case the uncertainty is expected to be slightly bigger due to the differences between (8) and (9) one can conclude that systematic error of 1% order is confirmed on the data as well.

14.5. Data/MC comparison. Although Monte-Carlo simulations are not used for the discovery claim it is needed for the cuts optimization and cosmic neutrino flux estimation after measurement is done. A comparison of the data/MC is done for the following precut:

- $\lambda > -6$
- $\beta < 1^\circ$
- nhits ≤ 10
- $t\chi^2 < b\chi^2$
• events reconstructed as up-going
• arriving from 3 off-zones

Where $\beta$ is the estimated reconstructed direction error and $1^{o}$ was chosen to be sure that probable signal events don’t penetrate to the off-zone and vice versa. The choice of the cut $t\chi^2 < b\chi^2$ is needed to get rid of the remaining sparking events. This cut is very efficient for this task as it was seen that it remains only 3% of the sparking events (the tests were done on the run 38347). Also it improves a lot the data/MC comparison in all energy range and what is more important - in the range of the high energies (3 events from the 10 with the highest estimated energy seemed suspicious on the event display and were identified as sparking with this cut). Cut on the up-going events is needed to reject the background from the atmospheric muons. The proposed cut on the events below horizon to decrease muon background seems to be redundant as the cut $beta < 1^{o}$ plus up-going events selection with later optimization on $\lambda$ is sufficient to consider the muon background as negligible.

The $\lambda$ distribution in fig. 26 shows that at $\lambda \sim -5.25$ there is a change of the main background component: for $\lambda < -5.3$ there are more muons and for $\lambda > -5.2$ there are more neutrinos. If one fits both areas a 13% lack of of muons and 27% excess of neutrinos is
Figure 27. $E_{ANN}$ distribution with data (black), sum of MC (red), $\nu_{atm}$MC (blue), $\mu$MC (yellow), $\nu$ from Fermi bubbles with cutoff 100TeV MC (green) for the precut.

seen in MC. Both effects can be a cumulative effect of the primary atmospheric particle fluxes arriving to the detector plus different efficiency of the detector in the MC.

The comparison of the ANN energy estimator for neutrinos is shown in fig. 27 for precut with a stricter cut $\lambda > -5.1$ to cut atmospheric muons. Also the cumulative distribution integrating from highest $\lambda$ is shown in fig.28.

It maybe seen that there is slightly higher energies for data events than for MC ones. This problem produces an additional increase of the data/MC ratio in a high energy region which is actually more correct to interpret as a ”shift” in a logarithmic energy scale. In order to tune MC the scale of 22% CHECK was applied first and then a fit of the shift with a step of the histogram bin size ($\log_{10}E = 0.1$) to find the best energy rescale. At the end the value of the shift $\log_{10}E = 0.2$ was used in further analysis together with the scale of 22%.

It is known that there is a 30% systematic uncertainty on the atmospheric neutrino flux so needed 22% normalization may be due the systematic uncertainty. Instead the lower reconstructed energy of the events in MC may be explained by the uncertainties in the water properties and probably by the PMT angular acceptance (however the later should
Figure 28. $E_{\text{ANN}}$ cumulative distribution of the events integrating from highest $\lambda$ with data (black), sum of MC (red), $\nu_{\text{atm}}$MC (blue), $\mu$MC (yellow), $\nu$ from Fermi bubbles with cutoff 100TeV MC (green) for the precut.

have minor impact on the up-going neutrinos). The proper tests are foreseen with Clancy James to prove this.

14.6. MRF optimization. Analysis was optimized to have minimum of the MRF (model rejection factor) which sets best limits in case of the no-discovery. The standard Feldman&Cousins approach was used to calculated the average upper limit. It is known that this method gives slightly lower limits than the proper calculation including the systematic error (as it will be discussed below) however as systematic error is low the current approach should be acceptable for the cuts optimization.

The chosen cut parameters were $\lambda$ and energy. The estimated energy is needed to reject the atmospheric neutrino background while $\lambda$ is needed mostly to cut atmospheric muons. Two different optimizations were done: in first signal and background were taken from MC (taking the average from the on-zone + off-zones to increase the statistics) and in the second the average of the data events in off-zones was used for the background together with the same signal as in the first method.

The table 29 below shows the cuts minimizing MRF for different energy cut offs. DESCRIPTION OF THE TABLE. It is noticeable that for the all cut choices the expected background in MC is in the very good correspondence with the average number of data
events in the off-zones which demonstrates the sanity of the scale and shift of the MC
energy distribution as explained in the previous section.

As it seen from the table cut optimized for the 100 TeV applies to the case with a
different cutoff the obtained MRF is comparable with the case when the optimization is
done for the appropriate cutoff. This shows that only one cutoff may be used for the cut
optimization which simplifies the analysis.

14.7. Limits calculation. After unblinding request the selected cut $\lambda > XX$, $E > YY$
will be applied on the data. From the 3 off-zones one measures Nbg events and from
the Fermi bubbles zone Nobs. Limits (upper/lower) on the signal expressed as number of
events are calculated with Bayesian approach for 90% C.L. using the likelihood

$$L(Nobs, Nbg|s, b, \tau, \sigma) = \text{Poisson}(Nobs|s + b)\text{Poisson}(Nbg|\tau * b)\text{Gaussian}(\tau|3, \sigma)$$

In case lower limits are not 0 it is possible to express the discovery in sigmas assuming
a Gaussian distribution of $\text{Gaussian}(N_{sign}N_{bg}/3, \text{stat} + \text{systerror})$.

The limits $(S_{\text{lower}}, S_{\text{upper}})$ calculated as number of events may be expressed as a flux
using MC. In order to do so $N_{\text{signal \_ MC}}$ for $A = 1.2 \times 10^{-7} E^2 GeV \ cm^{-2} s^{-1} sr^{-1}$ is calculated
applying cuts on the cosmic neutrino events in MC.

$$\Phi_{\text{limit}} = \frac{S_{\text{upper}}}{N_{\text{signal \_ MC}}} * A$$

This simple calculation is valid as the data/MC agreement after the tuning is very good.
To account for the 30% uncertainty in the atmospheric neutrino fluxes. $N_{\text{signal \_ MC}}$
should be varied from +30% to -30% and the worst limits should be presented as the final
result.

For the chosen cutl number of the observed background events in 3 off-zones is XXX.
For this number upper and lower limits are presented in fig. 30.


15. KM3Net

16. Conclusions

17. Acknowledgments

References

Figure 30. Limits for $N_{bg} = XXX$ calculated using the Bayesian approach with a flat signal prior and likelihood $\text{Poisson}(N_{obs} - s + b) \text{ Poisson}(N_{bg} - \tau \times b) \text{ Gaussian}(\tau - 3, \sigma)$. Upper limits are drawn with continuous line, lower - dotted.


18. Appendix A - Sparking run list

30658 31309 33608 33610 34663 34665 35467 36600 36666 36670 36689 38347 38348 38349 38351 38352 38353 38355 38357 38482 39192 41668 41671 42507 42509 42511 42513 42746 42915 42919 43196 43202 43206 43210 43215 43684 43996 44030 44035 44070 45242 46980 51036 53508 53851