Search for neutrinos from the Fermi Bubbles with the ANTARES telescope

S Hallmann and T Eberl on behalf of the KM3NeT collaboration

1 Erlangen Centre for Astroparticle Physics (ECAP), Friedrich-Alexander-Universität Erlangen-Nürnberg, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
E-mail: steffen.hallmann@fau.de, thomas.eberl@fau.de

Abstract. Two additional years of data (2014 and 2015, previous analysis: 2008–13) from the ANTARES neutrino telescope have been analysed using track-like event signatures from the Fermi Bubbles region. Six events are found in the signal region with a background expectation of 6.7 leading to more stringent upper limits for the signal flux. A benchmark study indicates that the sensitivity for the Fermi Bubble flux can be boosted when adding the shower channel to the analysis.

1. Introduction
The Fermi Bubbles are two giant lobes of γ-ray emission above and below the Galactic Centre, which have been identified in Fermi-LAT data in 2010 [1]. To date, the origin of these structures is still obscure. The measurement of a neutrino-flux – present only in hadronic emission scenarios – would therefore help to distinguish between the various proposed hadronic and leptonic scenarios. The deep-sea Cherenkov telescope ANTARES in the Mediterranean Sea has an excellent view for neutrinos from the Galactic Centre and the Fermi Bubbles’ region. A previous ANTARES search for a Fermi Bubble flux [2, 3] using 6 years of data taken between 2008 and 2013 has observed a small (1.9σ) yet intriguing excess in the signal region. This analysis adds two additional years of data, 2014 and 2015, to the analysis.

2. Neutrino flux expectation
In a purely hadronic emission scenario the neutrino flux follows the γ-ray flux, $\Phi_\nu(E) \sim \Phi_\gamma(E)$ [4]. Due to the dominant atmospheric neutrino background at low energies, ANTARES is only sensitive to a Fermi Bubble flux at TeV energies. The GeV-spectrum measured by Fermi-LAT (Fig. 1) is hence extrapolated to higher energies. Realistic sources within our galaxy are expected to accelerate particles up to 1 – 10 PeV. Since $\sim 20\%$ of the proton energy is on average converted into charged pions and this energy is distributed over four daughters in pion decay, exponential neutrino energy cut-offs with 50 TeV, 100 TeV and 500 TeV cut-off energy are probed in addition to the optimistic ‘no cut-off’ scenario. For the analysis two different γ-ray spectra – a hard $E^{-2}$ spectrum and an $E^{-2.18}$ spectrum which fits the Fermi-LAT flux at γ-energies above 10 GeV – are considered:

$$E^{\alpha} d\Phi_{\nu_e+\bar{\nu}_e} \over dE = A_{\text{model}}^\alpha \times \exp \left( -E / E_{\text{cut-off}}^\nu \right),$$

(1)
with flux normalisations for the two spectral indices $A_{\text{model}}^{2.0} = 1.2 - 2.4 \times 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ and $A_{\text{model}}^{2.18} = 1.8 - 3.6 \times 10^{-7} \text{GeV}^{1.18}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, respectively.

In this analysis, the $\gamma$-ray lobes observed by Fermi-LAT [5] are approximated by a leminiscate shape. The flux described in Eq. 1 is assumed to be homogeneous throughout the bubbles.

Background is determined from data using three off-zones shifted in time by $1/4$, $1/2$ and $3/4$ of a sidereal day (see Fig. 2) ensuring equal visibility of the on- and all off-zones. The difference in the number of expected events between on- and off-zones due to varying detection efficiencies and inhomogeneous data-taking was evaluated on simulated Monte Carlo data and is $\lesssim 3\%$.

3. Analysis of 2014/15 data and results from 8 years of track-like events

Due to varying environmental conditions a dedicated Monte Carlo simulation is produced on a run-by-run basis. For the analysis, only high quality runs which show good agreement between data and the corresponding Monte Carlo are considered. The analysed live-time in 2014 and 2015 amounts to 593 days. As in the previous analysis [2] a pre-selection of well-reconstructed, track-like events reconstructed as upward-going was applied. The final selection cuts on the track reconstruction quality parameter $\Lambda > -5.14$ to suppress atmospheric muons and the ANN energy estimator $\log_{10}(E_{\text{ANN}}) > 4.03$ to suppress atmospheric neutrinos were applied. The distributions of events in the off-zones are shown in Fig. 3. After cuts the 2014/15 data-set yields 6 events in the signal region and a background of $20/3 = 6.7$ events in the 3 off-zones.

Together with the previous years, a total live-time of 1765 days over the complete data taking period since the completion of the ANTARES detector (2008–2015) is now analysed. In total, 28 events are observed in the signal region and a background expectation from the three off-zones is $59/3 = 19.7$ events. The significance of the small overall excess in the signal region is evaluated using the method described by Li&Ma [6] and corresponds to a non-significant $1.5\sigma$. 90\% confidence level Feldman&Cousins upper limits [7] are presented in Fig. 4 for the different assumed spectra and cut-off energies. Note that the stated limits take into account statistical uncertainties only. The evaluation of systematic detector effects is currently on-going. Due to the absent excess of signal over background in 2014 and 2015 data, the stated limits are about a factor 2 more stringent than in the previous 6-year analysis [3].

4. Future inclusion of shower-like events

The TANTRA shower reconstruction algorithm can resolve TeV–PeV neutrinos with $\sim 2^\circ$ angular resolution and has recently been used in diffuse flux and point-source searches. To obtain a disjoint sample of events, all events passing the track-analysis selection criteria are discarded. As a benchmark, the pre-selection cuts used in the point-source search [8] have been applied. The final cut on the reconstructed shower energy $E_{\text{TANTRA}} \gtrsim 10^{4.5} \text{GeV}$ was optimised with the MRF technique [9] to give the most stringent upper limit using simulated Monte Carlo events from
Figure 3. Comparison of 2014/15 data and corresponding Monte Carlo in the off-zones for the $\Lambda$ track reconstruction quality (left) and the reconstructed energy (right) for $\Lambda > -5.14$.

Figure 4. 90% confidence level flux upper limits (solid lines) for different assumed Fermi Bubble signal spectra (shaded bands). Systematic uncertainties are not included.

the on- and off-zones. The resulting shower flux sensitivities for an $E^{-2}$ signal spectrum with these preliminary benchmark cuts and a live-time of 1600 days (similar to the track analysis) are only a factor of 1.1 (50 TeV cut-off) to 1.5 (no cut-off) above the track-channel upper limits presented in Fig. 4. The fact that this benchmark shower sensitivity is already at the same level as the current upper limits from the track channel indicates that a boost in sensitivity is possible from an all-flavour analysis of the Fermi Bubbles when combining the search for track- and shower-like events. In addition, the shower sensitivity can be improved further with a more rigorous cut optimisation.

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