Neutrinos from the milky way

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CONCLUSIONS AND OUTLOOK

When cosmic rays interact with the interstellar matter in our Galaxy, one of the particles that may be produced is the neutrino. Although the environmental conditions are very different, this is similar to how neutrinos are produced when cosmic rays interact with the atmosphere of the Earth. Not much is known yet about the Galactic neutrino signal and the only published result so far is a limit set by the AMANDA-II experiment [Kelley et al., 2005].

The ANTARES neutrino telescope is at a suitable location to perform a measurement of this neutrino flux, since it offers a good visibility of the region from where the highest signal is expected: the Galactic plane. The average flux in the region of interest for ANTARES is about a factor of 3 higher than in the region visible by AMANDA-II.

The analysis performed for this work consists of defining a signal region and a number of background regions. The background regions are used to determine the background from the data. Hence, no modelling is needed to estimate the background and the measurement is not affected by systematic uncertainties on the background. The background regions are constructed to have the same size and detector response as the signal region, so that the same number of background events is expected in each region.

Since the expected signal is too low compared to the background to make a discovery with ANTARES, the Model Rejection Factor (MRF) technique is used. The optimal signal region that is found in this way extends from a Galactic longitude of $-39°$ to $+39°$ and from a Galactic latitude of $-4.5°$ to $+4.5°$. It should be noted that the optimal size of the signal region depends on the angular distribution of the flux predicted by the models. Since the minimum of the MRF is quite shallow, fixing the optimal region found for a specific model makes the results for the other models slightly worse.

For the size of the signal region that is found to be optimal, 8 background regions can be defined, which are shown in Galactic coordinates in figure 5.5. Since the data taking of ANTARES is not continuous, the background regions may no longer be equivalent. To check for any biases, the effective visibility has been determined and compared to the theoretical visibility. It is found that the differences between the signal and background regions are at the level of 5‰. The compatibility of the background regions is verified by defining 35 cut intervals yielding 35 independent measurements per region. By comparing the number of events in each of these intervals for the 8 background regions, it is found that no systematic biases are present to within the statistical error of about 1%.

To enhance the sensitivity of ANTARES compared to other analyses performed so far, the TQ trigger is used in addition to the standard $3\mathrm{N} + 2\mathrm{T3}$ triggers (see section 4.2). The TQ trigger applies looser selection criteria and improves the detection efficiency for low energy neutrinos. The gain is about a factor of 2 below 30 GeV. It is also beneficial to use the TQ trigger at higher neutrino energies; the gain is about 20% compared to the standard triggers at 10 TeV.

However, since the TQ trigger only became operational at the end of 2009 and was only enabled when the conditions are suitable (i. e. the optical background is not too high), it is only active in 18.8% of the runs used for the data analysis. It should be noted that this fraction could be higher, since there is a subset of runs where the conditions are good, but the TQ trigger has not been enabled. If the TQ trigger would have been enabled, it would have been active in 27.8% of the runs. The expected gain for the diffuse Galactic neutrino flux is about 6% at trigger level when using the TQ trigger.

To further enhance the sensitivity, the R_{GF} parameter from GRIDFIT is used to reject misreconstructed atmospheric muons. The GRIDFIT reconstruction chain has been developed to improve the efficiency for low energy neutrinos ($\lesssim 100\,\mathrm{GeV}$). After optimising the quality cuts, the number of reconstructed neutrinos can be increased by about 20% compared to BBFIT, which is a reconstruction strategy used in current analyses focusing on low energy neutrinos (see section 4.3.1). In addition, GRIDFIT provides some information on the azimuth angle, which is not the case for single line BBFIT events. This is for example beneficial when trying to detect neutrinos from dark matter annihilations in the Sun.

Even though it was set out to be efficient at low energies, the performance at high energies is also good. The efficiency is almost as good as AAFIT (which is a reconstruction strategy used in analyses focusing on high energy neutrinos, see section 4.3.2) in most of the energy range, and better than AAFIT for the highest energies ($\gtrsim 3\,\mathrm{PeV}$), with an identical angular resolution. In the energy range of interest for this work, AAFIT outperforms GRID-

FIT by 3% to 7%. Therefore, AAFIT is used as the reconstruction strategy.

The R_{GF} parameter from GRIDFIT, which is related to the clustering of the hits, has proven to be effective in distinguishing upgoing neutrinos from misreconstructed atmospheric muons and can also be used in combination with other reconstruction strategies. It is most effective for low energy neutrinos. By taking the number of hits into account, the efficiency for high energy neutrinos can be increased as well, making it also suitable for a point source analysis.

After optimising the quality cuts, it is found that using the R_{GF} parameter increases the expected number of signal events from the Drift model by 21% compared to using the standard quality parameters (Λ, β and the reconstructed energy). This results in an improvement of the MRF by 1.4%. Using the TQ trigger in addition to the default $3\mathrm{N} + 2\mathrm{T}3$ triggers gives a 3% increase of the number of signal events expected from the Drift model, resulting in an improvement of the MRF of 0.6%.

After optimising the quality cuts (see equation 5.19), a total of 1324 events are found in the 8 background regions, 19 of which are triggered exclusively by the TQ trigger. This results in a background estimate for the signal region of 166 ± 5 and gives a (model independent) sensitivity of:

$$\Phi_{\nu_\mu+\bar{\nu}_\mu} = 3.2\, E_\nu^{-2.6}\, \mathrm{GeV}^{-1}\, \mathrm{m}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{s}^{-1}, \tag{7.1}$$

in the energy range from 0.18 TeV to 71 TeV. In this and the following equations, E_ν has units of GeV.

In the signal region a total of 177 ± 13 events are measured, of which 1 is triggered exclusively by the TQ trigger. This corresponds to a slight overfluctuation with a significance of $S = 0.8\sigma$. The measurement is thus compatible with the background-only hypothesis. The flux upper limits that can be set are:

$$\Phi_{\nu_\mu+\bar{\nu}_\mu} < 4.6\, E_\nu^{-2.6}\, \mathrm{GeV}^{-1}\, \mathrm{m}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{s}^{-1}, \tag{7.2}$$

for a spectral index of 2.6 and:

$$\Phi_{\nu_\mu+\bar{\nu}_\mu} < 10\, E_\nu^{-2.7}\, \mathrm{GeV}^{-1}\, \mathrm{m}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{s}^{-1}, \tag{7.3}$$

for a spectral index of 2.7, in the energy range from 0.15 TeV to 52 TeV.

The latter limit can be compared to the flux upper limit set by the AMANDA-II experiment, which is:

$$\Phi_{\nu_\mu+\overline{\nu}_\mu} < 4.8\, E_\nu^{-2.7}\,\mathrm{GeV}^{-1}\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}. \tag{7.4}$$

in the energy range from 0.2 TeV to 40 TeV.

The results can be found in figure 5.23, which shows the sensitivities and limits versus Galactic longitude. It can be seen that the ANTARES limit is a factor of 2.1 above the AMANDA-II limit. However, it should be pointed out that the sensitivity of ANTARES is 10% better than that of AMANDA-II. The difference in the limits is primarily caused by a combination of an overfluctuation measured by ANTARES and an underfluctuation measured by AMANDA-II.

Furthermore, it is important to note that a different region has been used as signal region by the AMANDA-II experiment: $33° < l < 213°$ and $-4.4° < b < 4.4°$, for which only the latitudinal extension has been optimised. The longitudinal extension has been chosen simply because this is the range of longitude values AMANDA-II can observe (around $b = 0°$). Since the size of the signal region used by AMANDA-II is a factor of about 2.3 bigger than that used in the ANTARES analysis, the AMANDA-II limit and sensitivity are lower. To really compare the results from both experiments, they should be compared to the expected signal fluxes in both regions. The average fluxes in the signal region used by AMANDA-II are on average a factor of about three lower than the fluxes in the signal region used in the ANTARES analysis, making the ANTARES limit, which specifically covers the inner Galactic plane region, the more stringent one.

The limits obtained here can also be used to say something about the origin of the flux measured by IceCube. Assuming a spectral index of 2.5, the hypothesis that all events measured by IceCube originate from the signal region can be rejected, since the required flux is a factor of about 1.9 higher than the obtained limit. Furthermore, the limit indicates that at most about 50% of the flux measured by IceCube can originate from the signal region considered here.

The current sensitivity is still more than a factor of 10 higher than the most optimistic model. Various options to improve the sensitivity of ANTARES (compared to standard analyses) have been investigated and when effective also implemented. A further possibility is to include the shower-like events created from electron- and tau-neutrino interactions and NC muon-neutrino interactions. Since the neutrino fluxes for all flavours are expected to be (nearly) the same due to oscillations, the useful signal could potentially be tripled (depending on the shower reconstruction efficiency). The worse angular resolution of shower events compared to track events is not a problem for this analysis, since the signal and background regions are large compared to the expected angular resolution.

With the inclusion of showers, the ANTARES neutrino telescope is still too small to detect a diffuse Galactic neutrino flux and a bigger neutrino telescope is required. The KM3NeT neutrino telescope is well suited for this measurement, since it offers the same high visibility of the region from where the highest signal is expected, but it is much larger than ANTARES.

The detection potential of KM3NeT is determined by using the same type of analysis as for ANTARES. The optimal size of the signal region is determined for KM3NeT using both the MRF and MDP techniques and is found to be almost identical to that found for ANTARES. For the calculation of the sensitivity, the same signal region is used so that the results can be directly compared.

The resulting sensitivity for 1 and 10 years of data taking with the full KM3NeT phase 2 detector is shown in figure 6.8. From the figure it can be seen that 1 year of data gives a sensitivity that is about 6.6 times better than the ANTARES sensitivity and a factor of about 4.4 better than the AMANDA-II limit.

Depending on the normalisation of the atmospheric neutrino flux, it takes about 2.7 to 4.3 years for KM3NeT to reach the level of the flux of the Drift model (see section 2.2) and about 4.4 to 7.0 years to reach that of the Fermi $\gamma \rightarrow \nu$ model (see section 2.3).

In addition to the sensitivity, the discovery potential of KM3NeT is determined. It is found that about 30 years are needed to reach a significance of 5σ (with 50% probability) for the claim of a discovery of the Drift model. Evidence for a new signal, i. e. a significance of 3σ, takes about 11 years. The results for the Fermi $\gamma \rightarrow \nu$ model are very similar; it takes about 11 (32) years to reach a significance of 3σ (5σ).

Considering the results of the diffuse flux analyses performed in ANTARES shows that including shower-like events can result in a sensitivity improvement of a factor of 2 compared to using only track-like events. In this case a significance of 3σ is reached for the Drift model after only 2.8 years of data taking of KM3NeT and a significance of 5σ after about 7.7. Again, the results for the Fermi $\gamma \rightarrow \nu$ model are similar; it takes 2.9 (8.1) years of taking data to reach a significance of 3σ (5σ). Further optimisation of the quality cuts, flavour identification of the neutrinos and usage of an energy estimator could potentially result in a further improvement.

It can be concluded that the measurement of the diffuse Galactic neutrino flux requires a combined track and shower analysis. Only then can the diffuse Galactic neutrino flux be seriously constrained after about 3 years of operation of the KM3NeT neutrino telescope.