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Hint for a TeV neutrino emission from the Galactic Ridge with the ANTARES telescope

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The central region of our Galaxy (Galactic Ridge) is expected to produce a neutrino flux comparable to the one detected in γ rays by Fermi, assuming these result from hadronic collisions of cosmic rays within the interstellar medium. Data collected by the ANTARES neutrino telescope between 2007 and 2020 are used to constrain this neutrino flux in the TeV energy range. Neutrino events reconstructed both as track-like and shower-like events are considered and the event selection is optimized for the search of an excess in the region of galactic coordinates $|l| < 30°$, $|b| < 2°$. The final energy distributions of selected events are inconsistent with the background-only expectation, estimated using off regions in the data, at 2σ level. The best-fit neutrino flux is compatible with the observed γ-ray flux from the Galactic Ridge, suggesting the presence of cosmic rays with energies up to the PeV range. The presentation will cover the details of the analysis strategy and results, as well as the prospects for future observations with the currently under-construction KM3NeT telescope.

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1. Introduction

The diffuse γ-ray emission from the Galactic Disk detected by Fermi Large Area Telescope (Fermi-LAT) extends up to TeV energies. This may indicate that the progenitor cosmic ray spectrum in the inner Galaxy may be harder than the spectrum measured at Earth. In the innermost part of the Disk, extending over galactic longitudes $|l| < 30-40^\circ$ and latitudes $|b| < 2-3^\circ$ and called the Galactic Ridge in the following, the spectrum may have a spectral index of $\Gamma = 2.4$ instead of the locally measured $2.7-3.0$. Cosmic rays interactions in the Galactic Ridge are also expected to induce a neutrino flux of the same intensity as the γ-ray one.

The ANTARES neutrino telescope [1], located in the depths of the Mediterranean Sea, has been operating between May 2008 and February 2022. It was composed of 12 vertical lines equipped with a total of 885 photomultiplier tubes (PMTs) arranged in triplets and distributed along the lines so that a volume of about $0.01\,\mathrm{km}^3$ was instrumented. Two main categories of neutrino events can be distinguished: track-like events correspond mostly to muon (anti-)neutrino charged-current interactions whose outgoing muon induces a long trail of Cherenkov light in the detector, allowing the precise reconstruction of the original neutrino direction; showering events are induced by other types of interaction associated with an electromagnetic cascade and thus producing a more diffuse light emission.

Previous searches performed with ANTARES have already constrained the neutrino emission from the Galactic Plane/Ridge region. In [2], the region within $|l| < 40^\circ$ and $|b| < 3^\circ$ was considered and limits were obtained using solely track-like events collected up to December 2013. Other searches have focused on the larger Galactic Plane region, especially considering the KRA-γ model, as in [3] for ANTARES and in [4] for the combination with IceCube.

This contribution summarises the results published recently in [5]. The updated search benefits from a larger data sample extending up to 2020 and including showering events and refined calibrations and energy estimators. It considers the Galactic Ridge region defined as $|l| < 30^\circ$ and $|b| < 2^\circ$.

2. Method

2.1 Event selection

Only track events reconstructed with a direction within the region $|l| < 30^\circ$, $|b| < 2^\circ$ and passing strict quality cuts are selected. For showering events, as the corresponding angular resolution is not as good as for tracks, the search region has been extended to $|l| < 33^\circ$, $|b| < 5^\circ$, which has been found to be the optimal region for the search of an $E^{-2.4}$ signal. The selection criteria are described in detail in [5].

The expected background is estimated using off-zone regions in the data with the same sky coverage as the search region but shifted in right ascension. The neutrino signal is simulated using the ANTARES Monte Carlo framework [6], assuming the signal is located within the Galactic Ridge and that it can be characterized by a single power-law spectrum: $\Phi(E) = \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = \Phi_0 \left(\frac{E_\nu}{E_0}\right)^{-\Gamma_\nu}$ where Γ_ν is the spectral index of the energy distribution, Φ_0 is the normalization of the neutrino flux for a single flavor, and E_0 is a convenient energy normalization, fixed to 40 TeV in the following.

2.2 Statistical analysis

The final measurements are represented as a function of the reconstructed neutrino energy $E_{\rm rec}$. For each event category, six bins are defined uniformly in logarithmic scale between $\log_{10}(E_{\rm rec}) = 2$ and 5. A Poisson likelihood is defined as:

$$\mathcal{L}\left(\{N_i\}; \{S_i^{(\Gamma_\nu)}\}, \{B_i\}, \Phi_0\right) = \prod_{i=1}^{12} \text{Poisson}\left(N_i, B_i + \Phi_0 S_i^{(\Gamma_\nu)}\right), \tag{1}$$

where N_i is the observed number of events in bin i, B_i is the corresponding expected background, $S_i^{(\Gamma_\nu)}$ is the signal prediction for $\Phi_0 = 1\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ and a spectral index Γ_ν, and the product runs over the twelve energy bins (6 for tracks, 6 for showers).

A Bayesian analysis is then applied to include statistical and systematic uncertainties on the background estimate and on the signal acceptance. Flat priors are assumed for Φ_0 and Γ_ν (with $1 \le \Gamma_\nu \le 4$). The marginalized posterior distribution is obtained after integrating over all nuisance parameters and is used to extract the best-fit point and 2D contours in the (Φ_0, Γ_ν) plane.

3. Results

The energy distributions are shown in Figure 1, indicating a slight excess with respect to the background-only expectation. The Bayesian study shows that the latter is rejected at 96% confidence level (2.0σ). Checks have been performed using alternative energy estimators and background estimate methods and the excess remains at a very similar level.

The 2D contours are shown in Figure 2. The best fit of ANTARES data corresponds to a per-flavor flux:

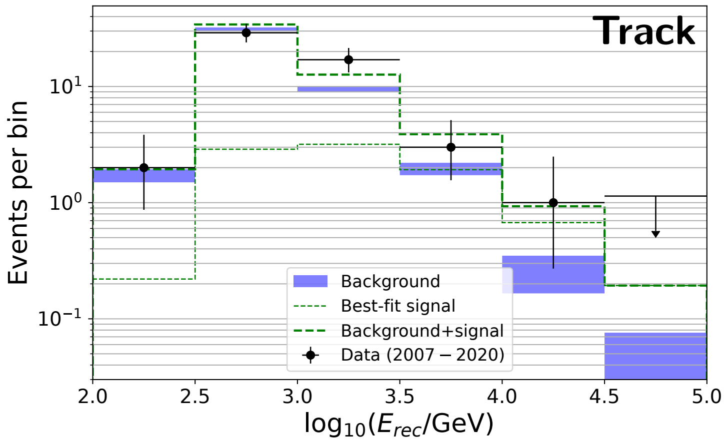
$$\begin{aligned} \Phi(1\,\text{GeV}) &= 7.6^{+5.0}_{-3.9} \times 10^{-5}\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}, \\ \Phi(40\,\text{TeV}) &= 4.0^{+2.7}_{-2.0} \times 10^{-16}\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}, \\ \Gamma_\nu &= 2.45^{+0.22}_{-0.34}. \end{aligned} \tag{2}$$

Profiling to the best-fit spectral index $\Gamma_\nu = 2.45$, the 90% credible interval ranges from $\Phi(1\,\text{GeV}) = 1.6 \times 10^{-5}$ to $1.7 \times 10^{-4}\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$.

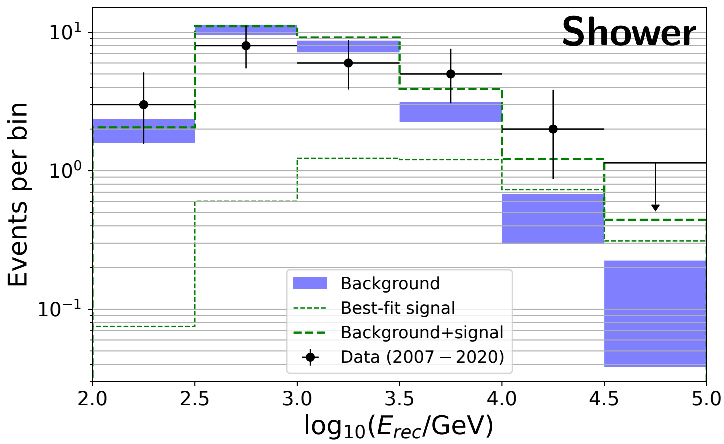
4. Discussion and outlooks

The analysis reported here shows an excess of ANTARES events from the Galactic Ridge direction consistent with the expected neutrino emission based on the γ-ray data collected by Fermi-LAT. The Figure 3 illustrates this comparison, where both γ-ray and neutrino constraints are shown. A simple pion decay model with a proton spectrum of spectral index $\Gamma_p = 2.4$ fits rather well Fermi-LAT data above 10 GeV. The corresponding expected neutrino emission is also displayed in the figure and is shown to be consistent with ANTARES constraints.

As the diffuse γ-ray flux from the Galactic Ridge may have contributions from other channels than pion decay, the normalization of the pion decay γ-ray and thus the corresponding neutrino flux may be lower. Furthermore, the cosmic-ray spectrum may have a cut-off at a few PeV, analogously to the break observed in the locally measured cosmic-ray spectrum, which would also be associated



(a) Track-like events



(b) Showering-like events

Figure 1: Reconstructed energy distribution for ANTARES track and shower samples [5]. The black dots represent the observation in the search region with its statistical errors at 68% confidence level, with the ANTARES dataset spanning from 2007 to 2020. The blue histogram illustrates the expected background estimated using the off-zone region, the vertical bands representing the corresponding statistical uncertainty. The thin dashed green line shows the best-fit Galactic neutrino signal and the thicker dashed green line is the sum of this best-fit signal and the background.

with a cut-off in the neutrino spectrum. The ANTARES measurement is still compatible with both these hypotheses, as illustrated on Figure 3 for the cut-off scenario. However, the analysis is not yet precise enough to conclude about the existence of these features.

The results can also be compared with the constraints presented by IceCube with the π^0 and KRAγ template models [10], and with the updated ANTARES template analysis using the most recent KRAγ models [11]. Direct comparison is hard as the template analyses cover the full sky and report flux in terms of the sky-integrated flux while the constraints derived in these proceedings are limited to the Galactic Ridge region and are per-steradian. The latter is thus scaled by the size of the Ridge region (~ 0.073 sr), no further correction is applied to account for the fraction

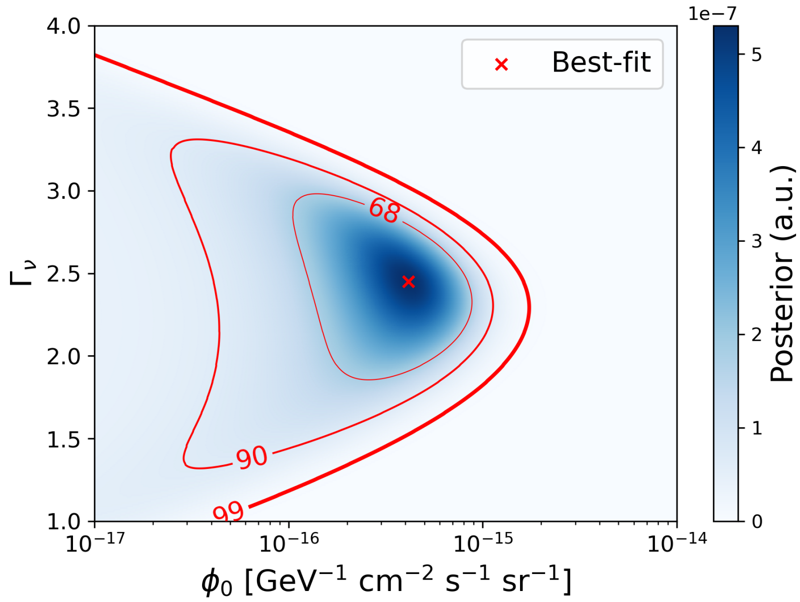


Figure 2: Marginalized posterior distribution in the plane ($\Phi(40\,\mathrm{TeV}) = \Phi_0, \Gamma_\nu$) [5]. The red lines show the 68%, 90%, and 99% contours of the probability, and the best-fit point is indicated by the cross.

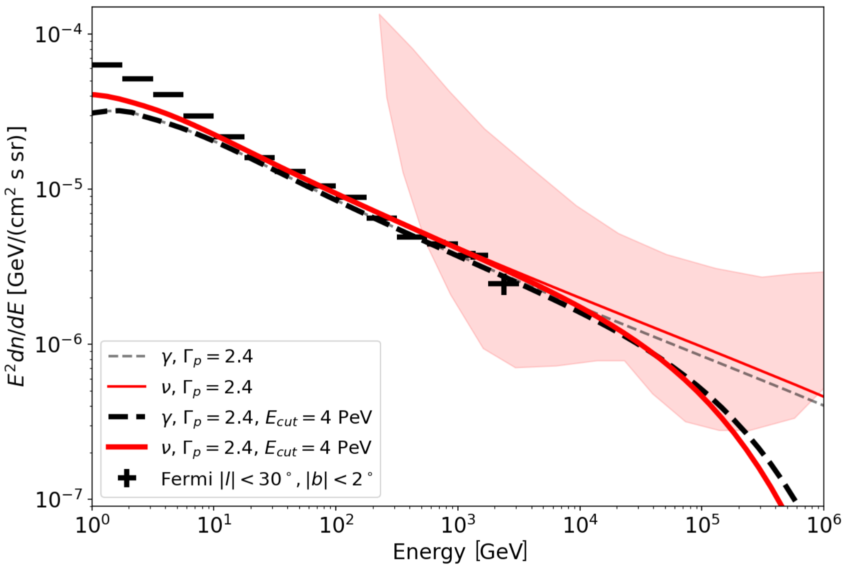


Figure 3: All-flavour neutrino flux corresponding to the 68% containment contour for the ANTARES excess (red shading) compared to the Fermi/LAT diffuse γ-ray flux (black data points) from the region $|l| < 30°$, $|b| < 2°$ [7]. Curves show model neutrino (solid) and γ-ray (dashed) pion decay spectra for different cosmic ray proton spectra: a power-law spectrum with slope $\Gamma_p = 2.4$ (thin) and one with the same spectral index and high-energy cut-off at $E_{cut} = 4\,\mathrm{PeV}$ (thick), as computed using the AAFrag software [8, 9].

of the template model that is contained in the Galactic Ridge. Compared to the whole Galactic diffusion emission, one should interpret the result from this analysis as if the Galactic Ridge was a naive template of the Galactic Plane with constant density in the Ridge and zero outside. Figure 4 summarises the various constraints on the Galactic neutrino emission within the aforementioned limitations: the different neutrino flux measurements are compatible and therefore start to provide a coherent picture of the neutrino emission from the Galaxy.

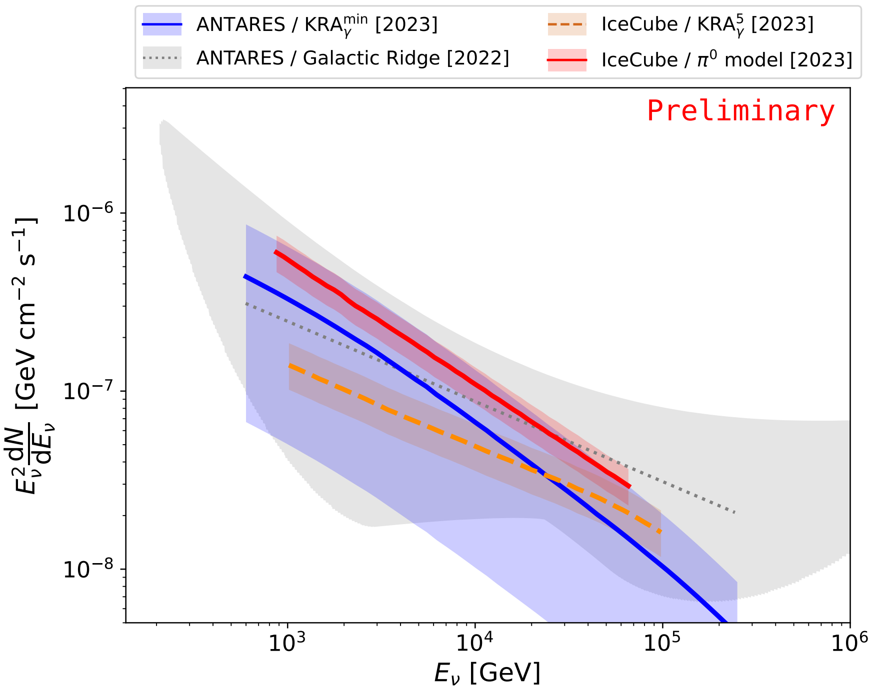


Figure 4: Energy-scaled, sky-integrated, per-flavor neutrino flux measured by ANTARES and IceCube. The lines show the best-fit flux normalization while the shaded regions indicate the 1σ uncertainties. The warm colors correspond to IceCube template analysis [10] The blue color corresponds to the latest KRA_γ^{min} ANTARES template analysis [11]. The grey color corresponds to ANTARES Galactic Ridge 68% contour integrated over the Ridge region ($\Delta\Omega = 0.073$ sr) [5].

Future observations with KM3NeT [12] will allow the community to better characterize this neutrino emission and the corresponding spectrum. Preliminary results have already been obtained with partial detector configurations [13] though it does not yet reach detection level. Multi-messenger studies in coordination with γ-ray facilities such as CTA and SWGO will help in linking the emissions in both messengers and hence fully determining the hadronic or leptonic nature of the diffuse γ-ray flux.

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