A multi-messenger study of the total galactic high-energy neutrino emission

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Abstract. A detailed multi-messenger study of the high-energy emission from the Galactic plane is possible nowadays thanks to the observations provided by gamma and neutrino telescopes. We show the potential of this approach by using the total gamma flux from the galactic plane measured by HESS at 1 TeV and in the longitude range $-75^\circ < l < 60^\circ$. We compare the HESS observational data with expectations for diffuse gamma emission, calculated by using different assumptions for the CR distribution in the Galaxy. We highlight the existence of an extended region of the galactic plane where the observed flux is substantially larger than the diffuse emission, thus calling for an additional contribution of comparable or larger intensity, possibly due to cumulative emission of resolved and unresolved gamma-ray sources. If this additional contribution is due to hadronic interactions, the considered region also produces a large neutrino flux and should be considered as a preferential target for the search of a galactic component in neutrino telescopes. We estimate the total contribution (i.e. including both diffuse and the source components) of this region to the IceCube HESE neutrino dataset as a function of the spectral index and energy cutoff of the sources, taking also into account the upper limit on galactic neutrino emission provided by Antares.

Keywords: neutrino astronomy, ultra high energy photons and neutrinos

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1 Introduction

During the last years the IceCube collaboration provided the first clear evidence of an astrophysical flux of High Energy (HE) neutrinos [1, 2]. The data collected in the energy range from 60 TeV to 10 PeV, called High Energy Starting Events (HESE), are consistent with an isotropic population of cosmic neutrinos having an energy distribution described by a power law with spectral index $2.93^{+0.33}_{-0.29}$ [3]. At present, no correlation of HESE arrival directions with the celestial positions of known astrophysical sources has been found [4]. The HESE data-set is dominated by showers events, characterised by poor angular resolution, and it is mainly sensitive to the southern sky that contains a large portion of the galactic plane and the galactic center. On the other hand, the upward-going muons which originate from the northern sky are better fitted by assuming a harder spectral index $2.13 \pm 0.13$ [2], so that a potential, despite still preliminary, tension exists between their energy distribution and that of the HESE. This scenario could be consistent with the presence of a soft galactic component which provides a relevant contribution in the southern sky in addition to a harder, isotropic extragalactic neutrino flux [5–9]. However, no evidence for a galactic component is found in the most recent dedicated analyses [10–12].

The existence of a non vanishing diffuse galactic contribution is guaranteed by hadronic interactions of HE Cosmic Rays (CR) with the gas contained in the galactic disk, through the production of charged pions (and kaons) that subsequently decay to neutrinos. In addition to this, HE neutrinos can be also produced by freshly accelerated hadrons colliding with the ambient medium within or close to an acceleration site. Hadronic interactions produce a roughly equal number of charged and neutral pions which decay to gamma rays. If photons are not absorbed by the intervening medium, we thus expect that the HE neutrino sky is strongly correlated with the HE gamma sky. This correlation provides us an handle to perform a detailed multi-messenger study of the galactic plane. The results of HE gamma observatories can be combined with the data collected by neutrino telescopes in order to test their consistence in a coherent scenario.

In 2014, the H.E.S.S. Galactic Plane Survey [13] provided the first detailed observation of the large-scale $\gamma$-ray emission in the inner region of the galactic plane at $E_\gamma \simeq 1$ TeV. The measured flux represents the global emission from known and unresolved sources, from diffuse $\gamma$-ray components and includes, in principle, the contributions of both hadronic and leptonic...
production mechanisms. In this paper, under the assumption that the observed HE photons are mainly produced by hadronic interactions and that they are not efficiently absorbed by the medium between the Earth and the production point, we use the HESS data to estimate the total HE neutrino flux from the galactic disk, as a function of the neutrino energy and arrival direction. This requires separating the sources contribution from the diffuse emission since the two components may have different spectral properties.

By comparing the HESS data with theoretical predictions for the diffuse $\gamma$–ray flux, we show that the source contribution dominates the $\gamma$ emission from the inner galactic region at 1 TeV and has a peculiar angular distribution that cannot be accounted by the diffuse component. This permits us to identify a “hot” extended region of the $\gamma$–ray sky which could be also an important source of HE neutrinos. Interestingly, this region approximately coincides with the portion of the galactic plane from which a $\sim 2\sigma$ excess of showers is observed in the HESE IceCube data sample. We estimate the expected $\nu$ flux from this region and we discuss the possibility to constrain neutrino sources emission parameters by considering the HESS IceCube data and the upper limits on a possible galactic component obtained by the Antares neutrino telescope [10].

2 The gamma/neutrino connection

The total fluxes of HE neutrinos and gammas produced in our Galaxy can be written as:

$$\varphi_{\gamma,\mathrm{tot}} = \varphi_{\gamma,\mathrm{diff}} + \varphi_{\gamma,S} + \varphi_{\gamma,\mathrm{IC}}$$
$$\varphi_{\nu,\mathrm{tot}} = \varphi_{\nu,\mathrm{diff}} + \varphi_{\nu,S}$$

(2.1)

where $\varphi_{\gamma,\mathrm{diff}}$ ($\varphi_{\nu,\mathrm{diff}}$) is the diffuse gamma (neutrino) flux produced by the interaction of CR with the gas contained in the galactic disk, $\varphi_{\gamma,S}$ ($\varphi_{\nu,S}$) is the gamma (neutrino) flux produced by sources and $\varphi_{\gamma,\mathrm{IC}}$ is the gamma flux produced through inverse compton by diffuse HE electrons.\(^1\) With the term “sources”, we refer here to the cumulative contribution from all resolved and unresolved (point-like or extended) objects.

Our goal is to estimate the total HE neutrino flux $\varphi_{\nu,\mathrm{tot}}$ from the galactic disk, as a function of the neutrino energy and arrival direction, taking advantage of the connection between gammas and neutrinos implied by hadronic interactions. In order to obtain $\varphi_{\nu,\mathrm{tot}}$, we have to evaluate separately the diffuse and the source contributions, since these two components have, in principle, different angular and spectral properties. The source contribution, in particular, being produced by freshly accelerated particles within or close to the acceleration site is expected to have a harder spectrum (apart from cut-off effects) and a less homogenous distribution than the diffuse component whose properties are instead determined by energy and spatial distributions of CR permeating the galactic disk.

The diffuse gamma and neutrino fluxes are calculated as it is described in the next section, by taking into account different assumptions for the CR distribution in the Galaxy. We compare the expectations for the diffuse gamma component with the observational determinations $\varphi_{\gamma,\mathrm{obs}}$ of the total gamma flux at 1 TeV obtained by the HESS detector. The purpose of this comparison is twofold. First, by requiring that $\varphi_{\gamma,\mathrm{obs}} \geq \varphi_{\gamma,\mathrm{diff}}$, we validate the adopted CR distributions, with implications for CR propagation models. Second, this permits us to obtain by subtraction the HE gamma flux produced by sources according to:

$$\varphi_{\gamma,S} \simeq \varphi_{\gamma,\mathrm{obs}} - \varphi_{\gamma,\mathrm{diff}}$$

(2.2)

\(^1\) We neglect possible contributions produced by DM annihilation or decay and/or the possible production of neutrinos and gammas in the galactic halo, being interested only in components that trace the galactic disk.
thus allowing us to determine the relative magnitude of $\varphi_{\gamma,S}$ and $\varphi_{\gamma,\text{diff}}$ at $E_\gamma = 1\ \text{TeV}$ as a function of the observation direction.

In the above expression, we assume as a working hypothesis that IC due to diffuse HE electrons provides a negligible contribution to the observed signal. This seems plausible considering that the galactic component is observed as the excess from the galactic plane with respect to the flux observed at larger galactic latitudes, automatically suppressing contributions with latitudinal intensity profiles which are significantly more extended than those derived by the gas distribution. In particular, the signal in HESS is obtained as the excess relative to the $\gamma$-ray emission at absolute latitudes $|b| \geq 1.2^\circ$ [13]; it has been evaluated that this implies a $\sim 95\%$ reduction of the celestial IC signal [13], assuming that this can be modeled by using the Fermi-LAT detected diffuse galactic emission, the GALPROP propagation code and the interstellar radiation field model as done in [14].

The neutrino flux emitted by sources is then estimated by taking advantage of the gamma/neutrino connection implied by hadronic interactions. We assume that the differential gamma flux is:

$$\varphi_{\gamma,S} = k_\gamma(\hat{n}_\gamma) \left( \frac{E_\gamma}{\text{TeV}} \right)^{-\alpha_\gamma} \exp \left( -\sqrt{\frac{E_\gamma}{E_{\text{cut},\gamma}}} \right)$$

(2.3)

where the normalization $k_\gamma$ is determined as a function of the observation direction $\hat{n}_\gamma$ by requiring that:

$$\varphi_{\gamma,\text{obs}}(\hat{n}_\gamma) - \varphi_{\gamma,\text{diff}}(E_{\text{obs}}, \hat{n}_\gamma) = k_\gamma(\hat{n}_\gamma) \left( \frac{E_{\text{obs}}}{\text{TeV}} \right)^{-\alpha_\gamma} \exp \left( -\sqrt{\frac{E_{\text{obs}}}{E_{\text{cut},\gamma}}} \right)$$

(2.4)

and the HESS observation energy is $E_{\text{obs}} = 1\ \text{TeV}$. If the gamma flux produced by sources is due to hadronic interactions through $\pi_0$ (and $\eta$ mesons) decays, then a comparable neutrino flux is produced by the same objects through charged pions and kaons decays. This can be expressed as a function of the neutrino energy $E_\nu$ and arrival direction $\hat{n}_\nu$ according to:

$$\varphi_{\nu,S} = k_\nu(\hat{n}_\nu) \left( \frac{E_\nu}{\text{TeV}} \right)^{-\alpha_\nu} \exp \left( -\sqrt{\frac{E_\nu}{E_{\text{cut},\nu}}} \right)$$

(2.5)

where the neutrino spectral index and energy cutoff are given by [15]:

$$\alpha_\nu = \alpha_\gamma$$

$$E_{\text{cut},\nu} = 0.59 E_{\text{cut},\gamma}$$

(2.6)

while the normalization constant can be obtained by using

$$k_\nu(\hat{n}_\nu) = (0.694 - 0.16\alpha_\gamma) \ k_\gamma(\hat{n}_\gamma = \hat{n}_\nu)$$

(2.7)

from the observational determination of the total gamma ray flux and the knowledge of the diffuse gamma ray component, see eq. (2.4).

The described approach represents a natural extension of previous analyses on the subject, see e.g. [16]. It has the advantage of naturally implementing a multi-component description of the total galactic emission which, as we shall see in the following sections, is required by HESS observational data. We remark that recent limits on the galactic HE neutrino emission by IceCube [11] and Antares [12] are obtained by using the expected energy and angular...
distributions of the diffuse component as a template for neutrino emission, thus implicitly assuming \( \varphi_{\nu} \gg \varphi_{\nu, S} \), in contrast with the findings of this paper.

Few additional comments are useful to further discuss some assumptions underlying our calculation. The parameterizations (2.3) and (2.5) are obtained in [15] by assuming that photons and neutrinos are produced through hadronic interactions by a CR population whose spectrum is well described by a power law with exponential cut-off. Here, we are considering the cumulative gamma and neutrino fluxes which are potentially produced by multiple (resolved and unresolved) sources. Hence, we are automatically assuming that the average spectrum of primary nucleons in the different sources is sufficiently well described by this functional form. It is possible, in principle, to adopt more refined approaches [17] that do not require specific parameterizations of the photon and neutrino flux. However, in consideration of the still incomplete knowledge of the sky at energies \( \sim 1 \) TeV or larger, we believe that it is advisable not to overcomplicate the model and to express the high energy neutrino and gamma emission in terms of two parameters, i.e. the neutrino spectral index \( \alpha_\nu \) and the cutoff \( E_{\text{cut},\nu} \) (or, equivalently, \( \alpha_\gamma \) and \( E_{\text{cut},\gamma} \)), which may depend in principle on the observation direction. Unless otherwise specified, we assume for simplicity that they can be considered constant in selected regions of the sky.

Finally, eqs. (2.6), (2.7) that connect the gamma and neutrino fluxes are obtained in the assumption that photons are produced in the different sources through hadronic mechanism, with negligible contribution of leptonic processes, and that they are not absorbed by the material between the production and the observation point. In the absence of specific observational evidence against this assumption, we take it as a working hypothesis with the goal of understanding the possibility to prove/disprove it with present and future neutrino telescopes.

3 The diffuse galactic components

The diffuse gamma and neutrino fluxes produced by the interaction of CR with the interstellar medium in the galactic plane can be written as:

\[
\varphi_{i, \text{diff}}(E_i, \hat{n}_i) = A_i \left[ \int_{E_i}^{\infty} dE \frac{\sigma(E)}{E} F_i \left( \frac{E_i}{E}, E \right) \right] \int_{0}^{\infty} dl \varphi_{\text{CR}}(E, r_\odot + l \hat{n}_i) n_H(r_\odot + l \hat{n}_i),
\]

where \( i = \nu, \gamma \) stands for neutrinos and gamma respectively while \( E_i \) and \( \hat{n}_i \) indicate the energy and arrival direction of the considered particles. The function \( \varphi_{\text{CR}}(E, \mathbf{r}) \) represents the differential CR flux, \( n_H(r) \) is the gas density distribution and \( r_\odot = 8.5 \) kpc is the position of the Sun. The total inelastic cross section in nucleon-nucleon collision, \( \sigma(E) \), is given by:

\[
\sigma(E) = 34.3 + 1.88 \ln(E/1 \text{ TeV}) + 0.25 \ln(E/1 \text{ TeV})^2 \text{ mb},
\]

where \( E \) is the nucleon energy, while the spectra \( F_i \left( E_i/E, E \right) \) of produced secondary particles are described (with 20% accuracy) by the analytic formulas given in [18]. The constant \( A_i \) is equal to 1 for photons and 1/3 for neutrinos. The one flavour neutrino flux \( \varphi_{\nu, \text{diff}} \) is indeed obtained by summing over the production rates of \( \nu_e \) and \( \nu_\mu \) in the sources, i.e.:

\[
F_{\nu} \left( E_i/E, E \right) \equiv F_{\nu_e} \left( E_i/E, E \right) + F_{\nu_\mu} \left( E_i/E, E \right),
\]

and then assuming flavour equipartition at Earth, as it is expected with good accuracy due to neutrino mixing, see e.g. [19].
Following our previous work [20], we consider different assumptions for the CR density in the Galaxy that are intended to cover the large uncertainty in CR propagation models. Namely, we assume that CR distribution is homogenous in the Galaxy (Case A), that it follows the distribution of galactic CR sources (Case B) and that it has a spectral index that depends on the galactocentric distance (Case C). These different assumptions permit us to relate the local determination of the CR flux, \( \varphi_{CR,\odot}(E) \), to the CR flux in all the regions of the Galaxy where the gas density is not negligible, according to:

\[
\varphi_{CR}(E, r) = \begin{cases} 
\varphi_{CR,\odot}(E) & \text{Case A} \\
\varphi_{CR,\odot}(E) g(r) & \text{Case B} \\
\varphi_{CR,\odot}(E) g(r) h(E, r) & \text{Case C}.
\end{cases}
\] (3.3)

For the CR flux at the Sun position, \( \varphi_{CR,\odot}(E) \), we consider the spectrum that was obtained in [6] by fitting the observational data of CREAM, KASCADE and KASCADE-Grande in the energy range \( E \sim 1 - 10^6 \) TeV in the assumption that the dominant contributions to the nucleon flux are provided by H and \(^4\)He nuclei.

The function \( g(r) \) is proportional to the CR source density and it is obtained from the SNRs distribution of [21], as reported in eq. (3.9) of [20]. The effect of this function is to increase the CR density in Case B by a factor \( \sim 4 \) at distances \( r = 2 - 3 \) kpc from the galactic center with respect to the local value. The function

\[
h(E, r) = \left( \frac{E}{E_p} \right)^{\Delta(r)}
\] (3.4)

introduces a position-dependent variation \( \Delta(r) \) of the CR spectral index in the Case C. The pivot energy in eq. (3.4) is taken as \( E_p = 20 \) GeV, since it is observed [22, 23] that the integrated CR density above 20 GeV roughly follows the function \( g(r) \) (i.e. the SNR distribution). For our calculations, we take:

\[
\Delta(r, z) = \Delta_0 \left( 1 - \frac{r}{r_\odot} \right)
\] (3.5)

with \( \Delta_0 = 0.3 \), for \( r \leq r_\odot \) (and zero elsewhere) in galactic cylindrical coordinates, that is intended to reproduce the trend of the spectral index with \( r \) observed by [22] at 20 GeV. This choice is equivalent to what is done by [24–26] in their phenomenological CR propagation model characterised by radially dependent transport properties. Indeed, our calculations for Case C well reproduce the results of the KRA\( \gamma \) model both for HE photons and neutrinos in the energy range of interest for this analysis.

By following previous prescriptions, we can estimate the diffuse fluxes of high energy neutrinos and gammas at the different energies of interest and as functions of the galactic latitude \( b \) and longitude \( l \). As described in our previous work [20], the diffuse fluxes are characterised by peculiar angular distributions. The maximal emission is always achieved for \( l \simeq \pm 25^\circ \) and \( b = 0^\circ \), but the fluxes may differ by large factors for \( |l| \leq 90^\circ \) in the three scenarios. To be quantitative, the diffuse gamma flux from the galactic center at \( E_\gamma = 1 \) TeV is larger by a factor \( \sim 2 \) and \( \sim 5 \) in Case B and C respectively, with respect to the value obtained in the assumption of uniform CR density (i.e. Case A).

\(^2\)In this work, we do not use the high energy approximation adopted in [20]. We retain both the energy and position dependence of the function \( h(E, r) \) in such a way that our calculations are valid for energies larger than \( \sim 10 \) GeV below which the parameterizations of [18] are no more valid.
The first detailed observation of the large-scale $\gamma$-ray emission in the inner region of the galactic plane has been performed by the HESS Galactic Plane Survey on 2014 [13]. HESS provides longitudinal and latitudinal profiles of the $\gamma$-ray emission at an energy $E_\gamma = 1$ TeV, in the range of galactic longitude $-75^\circ < l < 60^\circ$ and galactic latitude $-2^\circ < b < 2^\circ$. The observed flux includes known sources, unresolved sources and diffuse $\gamma$-ray emission, so that, following eq. (2.2), it can be used to estimate the sources contribution in this region of the galactic plane.

The grey dashed line in figure 1 shows the longitudinal profile of the total galactic emission observed by HESS. This is obtained by averaging the HESS data over an observation window $\Delta l \sim 15^\circ$, as emphasised by the horizontal error bar in the data points plotted in the figure. The re-binning of HESS data is done for several reasons; first, we are interested in the cumulative emission from a given region of the sky without necessity of distinguishing between the different (resolved and unresolved) sources in each angular bin; second, the re-binning procedure avoids large fluctuations thus making visually clear the excess in each region of the sky with respect of the diffuse gamma expectations; third, our goal is to estimate the total galactic signal in IceCube HESE dataset, which is dominated by showers with an average $15^\circ$ angular resolution, thus not requiring a particularly detailed map of the galactic plane emission.

In order to compare the HESS data with the diffuse gamma fluxes calculated in the previous section, we have to apply to our predictions the same background reduction procedure performed by the HESS collaboration and described in [13]. For each considered case, we thus calculate the excess along the galactic plane (i.e. in the region $|b| < 1.2^\circ$) with respect to the average emission in the region with $1.2^\circ < |b| < 2^\circ$. The obtained results are reported as a function of $l$ in figure 1 with a blue dotted line for Case A, a red dashed line for Case B and a black line for Case C. We see that the three considered scenarios are all consistent with observational data, being $\phi_{\gamma,\text{diff}} \leq \phi_{\gamma,\text{obs}}$ in the entire range of longitudes probed by HESS.

The requirement that the predicted diffuse emission does not exceed the observed flux can be used to constrain the magnitude of the CR spectral hardening in Case C. The nu-
merical coefficient $\Delta_0$ in eq. (3.5), that physically corresponds to the difference between the CR spectral index at the galactic center and at the Sun position, should be less than 0.4 to avoid that $\varphi_{\gamma, \text{diff}} \geq \varphi_{\gamma, \text{obs}}$ for $l \simeq 0^\circ$. In our calculations, the value $\Delta_0 = 0.3$ is adopted as a reference value since it reproduces the trend of the CR spectral index observed by [22].

It should be noted that diffuse emission does not saturate the HESS observed signal, even when the most favourable Case C is considered, thus requiring an additional contribution of comparable or larger intensity from resolved and unresolved sources. Namely, $\varphi_{\gamma, \text{S}} = \varphi_{\gamma, \text{obs}} - \varphi_{\gamma, \text{diff}}$ accounts for 89%, 76% and 50% of the gamma flux observed at $E_\gamma = 1\text{ TeV}$ in the longitude range $-75^\circ \leq l \leq 60^\circ$ in Case A, Case B and Case C, respectively. This is larger than what is obtained at lower energies. At $E_\gamma \sim 1\text{ GeV}$, it was e.g. estimated that resolved and unresolved sources account for less than $\sim 15\%$ of the total galactic emission measured by Fermi-LAT [27]. The larger contribution of sources at high energy can be naturally explained by considering that sources are expected to have harder spectrum than the diffuse component.

We finally see that the gamma-ray emission has a distinctive angular distribution which is different from that of the diffuse component: a fraction equal to 50% of this emission is concentrated in a broad peak with $11^\circ < l < 57^\circ$ and $|b| < 2^\circ$. In the following, we refer to this specific range of galactic coordinates as the Extended Hot Region (EHR) of the gamma sky. It is evident that this region should be a preferential target for the search of a galactic component in neutrino telescopes; if (part of) the observed emission is due to hadronic interactions, then this portion of the sky is also emitting a large flux of high energy neutrinos. As shown in figure 1, only a fraction of the EHR (not containing the maximum of the expected emission) is contained in the Northern sky.

Other experiments observe the galactic TeV gamma-ray emission beside HESS. We do not include them in the present analysis because they do not cover the same range of galactic longitudes and latitudes than HESS and/or they do not have a comparable statistical accuracy. The ground based MILAGRO [28] and Argo-YBJ [29] provide e.g. a determination of galactic emission at $E_\gamma = 15\text{ TeV}$ for $30^\circ \leq l \leq 110^\circ$ and $|b| \leq 2^\circ$ and at $E_\gamma = 0.6\text{ TeV}$ for $25^\circ \leq l \leq 100^\circ$ and $|b| \leq 5^\circ$, respectively. They thus probe only partially the EHR region and with a different latitudinal cut than HESS. The Fermi-LAT satellite is observing the entire sky; however, due to the small collection area has a limited statistic above 1 TeV. By using the Fermi-LAT Pass8 data, ref. [30] selected 97 events with $E_\gamma \geq 1\text{ TeV}$ and latitude $|b| \leq 5^\circ$ in about 7 years data. The collected data sample is not sufficiently large to compare with HESS results.

5 The total galactic neutrino emission

The IceCube detector probes the inner galactic region by using the HESE data set, firstly described in [1], that now includes 80 events collected during 2078 days of data taking [3]. These events are compatible with an isotropic best-fit flux $E_\nu^{-2}\varphi_{\nu, \text{iso}} = 2.46 \pm 0.8 \times 10^{-8}(E_\nu/100\text{ TeV})^{-0.92}\text{ GeV cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}$. It is interesting to compare the number of HESE

\footnote{The adopted latitudinal cut implies a different contamination from Inverse Compton, making thus impossible to compare results from different experiments on homogenous ground.}

\footnote{The Fermi-LAT gamma-ray data at lower energies ($E_\nu \leq 1\text{ TeV}$) are used in [16] to estimate the galactic neutrino emission. No comparison of observational data with diffuse gamma predictions is performed and, thus, diffuse and source contributions are not disentangled. It is, however, observed that $\gamma$-ray data from the galactic ridge are well fitted by a broken power law with a hardening at high energies, as it is naturally expected in the presence of two components of comparable intensities below 1 TeV with different spectral indexes, in agreement with the scenario emerging from this work.}
produced by this flux (and background components) with observed events in a region of the sky compatible with the EHR of gamma ray emission. Since the HESE data set is mainly composed by showers, characterised by an average angular uncertainty of $\sim 15^\circ$, we define the observation window $|b| < 15^\circ$ and $11^\circ < l < 57^\circ$ that corresponds to the red box in figure 2. Note that the adopted longitude range is determined by the condition that it contains 50% of the gamma-ray emission observed by HESS, while the latitude interval corresponds to the adopted shower angular resolution. The observation window is, thus, defined a priori and it is not optimized for the search of an excess.\footnote{The search for an excess from a generic region of the sky over the predictions obtained for an isotropic neutrino flux requires a different statistical treatment and it is beyond the scope of this paper.}

In the selected observation window, $N_{\text{Sh,obs}} = 5$ shower events (and no tracks) are observed; all of them have a relatively low reconstructed energy $E_{\text{dep}} \sim 30$ TeV, except for one event with $E_{\text{dep}} \sim 400$ TeV. The number of observed showers should be compared with expectations from the atmospheric neutrino background\footnote{We do not include the atmospheric muon background because this mainly contributes to track events which are not observed in the considered observation window.} and from the isotropic neutrino flux $\varphi_{\nu,\text{iso}}$ which explains the bulk of IceCube HESE data. The atmospheric neutrino background accounts for $\sim 15.6$ events (showers + tracks) in the whole sky. The number of showers in the considered observation window can be estimated by using the angular distribution of atmospheric neutrino events for $E_{\text{dep}} > 30$ TeV reported in figure 5 of the Supplementary Materials of [31] and by considering that showers are expected to be 31% of the total events. As a final result, we obtain $N_{\text{Sh,atmo}} \sim 0.3$ from this background source, i.e. much lower than the observed number.

The contribution of astrophysical components (either extragalactic or galactic) is estimated by considering that the angular distribution of shower events can be calculated as (see [20] for details):

$$\frac{dN_{\text{Sh}}(\hat{n})}{d\Omega} = T \int dE_{\nu} \int d\Omega_{\nu} G_{\text{Sh}}(\hat{n}, \hat{n}_{\nu}) \varphi_{\nu}(E_{\nu}, \hat{n}_{\nu})$$

$$\times [A_{\nu}(E_{\nu}, \hat{n}_{\nu}) + A_{\mu}(E_{\nu}, \hat{n}_{\nu}) (1 - \eta) + A_{\tau}(E_{\nu}, \hat{n}_{\nu})],$$

\hspace{1cm} (5.1)
Figure 3. The number of showers produced by the total (diffuse + sources) galactic neutrino flux in IceCube in the indicated observation window for Case A (upper panel), Case B (middle panel) and Case C (lower panel). The shaded areas show the regions of the plane ($E_{\text{cut},\nu}$, $\alpha_{\nu}$) excluded by Antares.
where \( \hat{n} \) is the observation direction, \( T \) is the observation time, \( A_i(E_\nu, \hat{n}_\nu) \) are the effective areas for the HESE data sample [32] and the parameter \( \eta = 0.8 \) gives the probability that a muonic neutrino produces a track event [19]. The function \( G_{\text{Sh}} \) is the showers angular resolution, i.e.

\[
G_{\text{Sh}}(\hat{n}, \hat{n}_\nu) = \frac{m}{2\pi \delta n_{\text{Sh}}} \exp\left(-\frac{1-c}{\delta n_{\text{Sh}}^2}\right)
\]

where the parameter \( m \) is a normalisation factor, \( c \equiv \cos \theta = \hat{n} \cdot \hat{n}_\nu \) describes the angle between the true (\( \hat{n}_\nu \)) and reconstructed (\( \hat{n} \)) neutrino direction and the width \( \delta n_{\text{Sh}} \) is calculated by requiring that \( \theta \leq 15^\circ \) at 68.3% C.L. By using the above prescription, we estimate that the isotropic best fit astrophysical neutrino flux accounts for \( N_{\text{Sh,iso}} \sim 1.4 \) showers in the considered observation window. In conclusion, we have an excess of \( \Delta N_{\text{Sh}} = N_{\text{Sh,obs}} - N_{\text{Sh,atmo}} - N_{\text{Sh,iso}} \sim 3.3 \) showers that requires a \( \sim 2\sigma \) upward fluctuation of the expected counting rate in order to be explained in terms of the isotropic best fit astrophysical neutrino flux (and background) only, and that could be a potential indication in favour of a galactic contribution.

In view of the above results, we investigate whether the total galactic emission (i.e. diffuse + sources) can provide a relevant contribution to the observed IceCube signal, compatibly with the upper limit on the galactic component provided by Antares. The total galactic neutrino flux is estimated as a function of the isotropic neutrino energy and arrival direction as explained in section 2. The neutrino angular distribution is fully determined by HESS observational data, see eqs. (2.4), (2.7), while the energy distribution depends on the spectral index \( \alpha_\nu \) and the energy cut-off \( E_{\text{cut,}\nu} \) of the sources. The coloured lines in figure 3 correspond to a fixed number of shower events in IceCube produced by the total galactic component in the region \( |b| < 15^\circ \) and \( 11^\circ < \ell < 57^\circ \) and during the observation time of 2078 days. The three panels are obtained by calculating the diffuse neutrino contribution as prescribed by Case A, Case B and Case C, respectively. Not surprisingly, the total numbers of events produced in the three cases are comparable, since the total gamma flux at 1 TeV is observationally fixed by HESS (and implemented in our calculations). However, the events are differently distributed among source and diffuse component with a maximum (minimum) from the diffuse emission equal to 1.5 (0.4) in Case C (Case A).

The Antares neutrino telescope performed a detailed analysis of neutrino production from the central region of the galactic plane, i.e. \( |\ell| < 40^\circ \) and \( |b| < 3^\circ \), corresponding to the green dashed box in figure 2, by using track-like events observed from 2007 to 2013 [10]. No excess of events from the galactic ridge has been detected and 90% upper limits on the galactic contribution averaged over the observation region have been set as a function of the neutrino spectral index.\(^7\) For \( \alpha_\nu = 2.4 \), the 90% C.L. upper limit at 100 TeV corresponds to \( \varphi_\nu(100 \text{ TeV}) = 2.0 \times 10^{-17} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) which is about a factor 2 larger than what predicted for the galactic diffuse component in Case C. If we assume that the sources emission parameters are approximately constant in the EHR and in the Antares observation window, we can implement the Antares bound in the plane \( (E_{\text{cut,}\nu}, \alpha_\nu) \), excluding the shaded areas shown in the three panels of figure 3.

We see that significant constraints are obtained from Antares for \( \alpha_\nu \leq 2.3 \); e.g. the possibility of a spectral index \( \alpha_\nu = 2.0 \) and cutoff energy \( E_{\nu} \geq 30 \text{ TeV} \) is excluded for all considered scenarios. However, the Antares limit does not exclude the possibility that galactic emission could produce a non negligible event number in the IceCube HESE data sample.

\(^7\)We do not consider the more recent bounds provided by Antares [12] and IceCube [11] because they are obtained by using the KRA-\( \gamma \) model as template for galactic emission and cannot thus be applied to constrain the total galactic emission (source + diffuse) which has a different angular and energy distribution.
Indeed, up to $\sim 3$ shower events can be produced by galactic neutrinos emitted from the EHR, compatibly with the Antares bound and possibly accounting for a large fraction of the excess $\Delta N_{sh} = 3.3$ reported by IceCube.

6 Discussion

In this paper, we perform a multi-messenger study of the total galactic high-energy neutrino emission. By comparing the $\gamma$-ray observational data from HESS Galactic Plane Survey with the predicted diffuse galactic emission, we highlight the existence of an extended hot region (EHR) of the gamma sky ($11^\circ < l < 57^\circ$) where the cumulative sources contribution dominates over the diffuse component. From the same portion of the galactic plane (with a latitudinal cut $|b| \leq 15^\circ$ that takes into account the shower angular resolution), we observe a $\sim 2\sigma$ upward fluctuation of shower events in the HESE IceCube dataset with respect to the predictions obtained for the isotropic best fit astrophysical neutrino flux. Incidentally, the TeVCat catalogue [33] contains about 20 unidentified $\gamma-$sources in this region (most of them newly announced).

We investigate whether the total galactic emission (i.e. diffuse + sources) can provide a relevant contribution to the observed HESE IceCube signal. We show that the upper limit on the galactic contribution from Antares already provides significant constraints. However, it exists a region of the sources emission parameters (see figure 3) that may explain the small excess of shower events from EHR observed by IceCube. Dedicated analysis from Antares and IceCube to rule out this possibility could be extremely interesting.

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References

[1] ICECUBE collaboration, M.G. Aartsen et al., Evidence for high-energy extraterrestrial neutrinos at the IceCube detector, Science 342 (2013) 1242856 [arXiv:1311.5238] [INSPIRE].

[2] ICECUBE collaboration, M.G. Aartsen et al., Observation and characterization of a cosmic muon neutrino flux from the northern hemisphere using six years of IceCube data, Astrophys. J. 833 (2016) 3 [arXiv:1607.08006] [INSPIRE].

[3] ICECUBE collaboration, C. Kopper, Observation of astrophysical neutrinos in six years of IceCube data, PoS(ICRC 2017)981.

[4] ICECUBE collaboration, M.G. Aartsen et al., Search for astrophysical sources of neutrinos using cascade events in IceCube, Astrophys. J. 846 (2017) 136 [arXiv:1705.02383] [INSPIRE].

[5] P.B. Denton, D. Marfatia and T.J. Weiler, The galactic contribution to IceCube’s astrophysical neutrino flux, JCAP 08 (2017) 033 [arXiv:1703.09721] [INSPIRE].

[6] M. Ahlers, Y. Bai, V. Barger and R. Lu, Galactic neutrinos in the TeV to PeV range, Phys. Rev. D 93 (2016) 013009 [arXiv:1505.03156] [INSPIRE].

[7] A. Neronov and D.V. Semikoz, Evidence the galactic contribution to the IceCube astrophysical neutrino flux, Astropart. Phys. 75 (2016) 60 [arXiv:1509.03522] [INSPIRE].
[8] A. Palladino and F. Vissani, *Extragalactic plus galactic model for IceCube neutrino events*, *Astrophys. J.* **826** (2016) 185 [arXiv:1601.06678] [INSPIRE].

[9] A. Palladino, M. Spurio and F. Vissani, *On the IceCube spectral anomaly*, *JCAP* **12** (2016) 045 [arXiv:1610.07015] [INSPIRE].

[10] ANTARES collaboration, S. Adrian-Martinez et al., *Constraints on the neutrino emission from the galactic ridge with the ANTARES telescope*, *Phys. Lett. B* **760** (2016) 143 [arXiv:1602.03036] [INSPIRE].

[11] IceCube collaboration, M.G. Aartsen et al., *On the IceCube spectral anomaly*, *JCAP* **12** (2016) 045 [arXiv:1610.07015] [INSPIRE].

[12] ANTARES collaboration, A. Albert et al., *New constraints on all flavor galactic diffuse neutrino emission with the ANTARES telescope*, *Phys. Rev. D* **96** (2017) 062001 [arXiv:1705.00497] [INSPIRE].

[13] H.E.S.S. collaboration, A. Abramowski et al., *Diffuse galactic gamma-ray emission with H.E.S.S.*, *Phys. Rev. D* **90** (2014) 122007 [arXiv:1411.7568] [INSPIRE].

[14] Fermi-LAT collaboration, M. Ackermann et al., *Fermi-LAT observations of the diffuse gamma-ray emission: implications for cosmic rays and the interstellar medium*, *Astrophys. J.* **750** (2012) 3 [arXiv:1202.4039] [INSPIRE].

[15] A. Kappes, J. Hinton, C. Stegmann and F.A. Aharonian, *Potential neutrino signals from galactic gamma-ray sources*, *Astrophys. J.* **656** (2007) 870 [Erratum ibid. **661** (2007) 1348] [astro-ph/0607286] [INSPIRE].

[16] A. Neronov, D.V. Semikoz and C. Tchernin, *PeV neutrinos from interactions of cosmic rays with the interstellar medium in the galaxy*, *Phys. Rev. D* **89** (2014) 103002 [arXiv:1307.2158] [INSPIRE].

[17] F.L. Villante and F. Vissani, *How precisely neutrino emission from supernova remnants can be constrained by gamma ray observations?*, *Phys. Rev. D* **78** (2008) 103007 [arXiv:0807.4151] [INSPIRE].

[18] S.R. Kelner and F.A. Aharonian, *Energy spectra of gamma-rays, electrons and neutrinos produced at interactions of relativistic protons with low energy radiation*, *Phys. Rev. D* **78** (2008) 034013 [Erratum ibid. **D 82** (2010) 099901] [arXiv:0803.0688] [INSPIRE].

[19] A. Palladino, G. Pagliaroli, F.L. Villante and F. Vissani, *What is the flavor of the cosmic neutrinos seen by IceCube?*, *Phys. Rev. Lett.* **114** (2015) 171101 [arXiv:1502.02923] [INSPIRE].

[20] G. Pagliaroli, C. Evoli and F.L. Villante, *Expectations for high energy diffuse galactic neutrinos for different cosmic ray distributions*, *JCAP* **11** (2016) 004 [arXiv:1606.04489] [INSPIRE].

[21] D.A. Green, *Constraints on the distribution of supernova remnants with galactocentric radius*, *Mon. Not. Roy. Astron. Soc.* **454** (2015) 1517 [arXiv:1508.02931] [INSPIRE].

[22] Fermi-LAT collaboration, F. Acero et al., *Development of the model of galactic interstellar emission for standard point-source analysis of Fermi Large Area Telescope data*, *Astrophys. J. Suppl.* **223** (2016) 26 [arXiv:1602.07246] [INSPIRE].

[23] S. Recchia, P. Blasi and G. Morlino, *On the radial distribution of galactic cosmic rays*, *Mon. Not. Roy. Astron. Soc.* **462** (2016) L88 [arXiv:1604.07682] [INSPIRE].

[24] D. Gaggero, A. Urbano, M. Valli and P. Ullio, *Gamma-ray sky points to radial gradients in cosmic-ray transport*, *Phys. Rev. D* **91** (2015) 083012 [arXiv:1411.7623] [INSPIRE].

[25] D. Gaggero, D. Grasso, A. Marinelli, A. Urbano and M. Valli, *The gamma-ray and neutrino sky: a consistent picture of Fermi-LAT, Milagro and IceCube results*, *Astrophys. J.* **815** (2015) L25 [arXiv:1504.00227] [INSPIRE].
[26] D. Gaggero, D. Grasso, A. Marinelli, M. Taoso and A. Urbano, Diffuse cosmic rays shining in the galactic center: a novel interpretation of H.E.S.S. and Fermi-LAT γ-ray data, Phys. Rev. Lett. 119 (2017) 031101 [arXiv:1702.01124] [nSPIRE].

[27] Fermi-LAT collaboration, F. Acero et al., Fermi Large Area Telescope third source catalog, Astrophys. J. Suppl. 218 (2015) 23 [arXiv:1501.02003] [nSPIRE].

[28] A.A. Abdo et al., A measurement of the spatial distribution of diffuse TeV gamma ray emission from the galactic plane with Milagro, Astrophys. J. 688 (2008) 1078 [arXiv:0805.0417] [nSPIRE].

[29] ARGO-YBJ collaboration, B. Bartoli et al., Study of the diffuse gamma-ray emission from the galactic plane with ARGO-YBJ, Astrophys. J. 806 (2015) 20 [arXiv:1507.06758] [nSPIRE].

[30] M.D. Kistler, On TeV gamma rays and the search for galactic neutrinos, arXiv:1511.05199 [nSPIRE].

[31] IceCube collaboration, M.G. Aartsen et al., Observation of high-energy astrophysical neutrinos in three years of IceCube data, Phys. Rev. Lett. 113 (2014) 101101 [arXiv:1405.5303] [nSPIRE].

[32] Search for contained neutrino events at energies above 30 TeV in 2 years of data, https://icecube.wisc.edu/science/data/HE-nu-2010-2012, released 21 November 2013.

[33] TeVCat 2 webpage, http://tevcat2.uchicago.edu/.