A reinvestigation into the diffuse neutrino flux from the inner Galaxy in light of new very high energy γ-ray observations

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Abstract. In light of the recent MILAGRO collaborations publication of the detection of diffuse multi-TeV emission from a region close to the inner Galaxy, we reinvestigate the diffuse neutrino flux calculation from this region. Conventional determinations of the diffuse neutrino flux following cosmic ray propagation through the Galaxy, tuned to reproduce the locally observed cosmic ray spectrum, give rise to diffuse fluxes that are significantly below the detected diffuse flux. Assuming that this excess is hadronic in origin and is emitted by the entire inner Galactic region, we determine the diffuse neutrino flux expected from a region of the Galactic disk with coordinates $-40^\circ < l < 40^\circ$. The calculated diffuse flux of neutrinos, for this hadronic only scenario, is found to be detectable by a km^3–scale detector located in the northern hemisphere.

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INTRODUCTION

Recently, the MILAGRO collaboration reported upon the detection of multi-TeV diffuse γ-ray emission from two regions in the Galactic plane: the Cygnus region (located at galactic longitude $65^\circ < l < 85^\circ$) [1] and the portion of the inner Galaxy visible from the location of MILAGRO ($30^\circ < l < 65^\circ$) [2]. When placed alongside earlier lower energy measurements by EGRET [3], such detections provide an interesting insight into both the spatial and energy distributions of Galactic cosmic rays (CR).

The diffuse GeV emission detected by EGRET along the galactic plane is believed to be the result of hadronic interactions between CRs and interstellar material. A strong point in favor of this hypothesis is the correlation of the diffuse GeV emission with the spatial distribution of the interstellar gas, constituting the target material for CR interactions [3]. The same argument might be extended also to the diffuse multi-TeV emission detected by MILAGRO, since both the Cygnus region and the inner Galaxy are characterised by an enhanced gas densities. In the case of the Cygnus region, the morphology of the multi-TeV emission correlates with the CO emission, a tracer of gas density. This again is suggestive of a hadronic origin also for the very high energy diffuse emission [1]. Similarly, for the region close to the inner Galaxy, the rather narrow latitude profile of the multi TeV-emission, concentrated around the dense Galactic disk, might suggest a hadronic interpretation of the γ-ray data, though a leptonic one could also be feasible [4, 5, 2].

In the past, several calculations of the diffuse neutrino flux from the Galactic plane region have been published. The simplest of these approaches assumes the CR distribution is constant across the Galactic disk [6, 7, 8], with more sophisticated calculations assuming a distribution of CR sources in the disk and obtaining a steady state CR distribution by solving the diffusion equation [9, 10]. All of these approaches, however, result in relatively small neutrino fluxes, below that required to be detectable by km^3-size neutrino detectors such as IceCube or KM3NeT, within one year of data acquisition. However, no a priori reason exists that such a CR spectrum is applicable throughout the Galaxy. Indications exist for a departure from the locally observed CR spectral index of $\sim E^{-2.7}$ in the diffuse γ-ray emission observed by H.E.S.S. from the Galactic centre ridge [11] and the GeV excess in the diffuse flux from the Galaxy observed in EGRET data, which might be due to a CR spectrum harder than the one observed at Earth [12, 4].

Here we adopt a phenomenological approach, assuming the multi-TeV diffuse flux observed by MILAGRO is produced through hadronic interactions. This model requires the assumption of a harder CR spectrum in the inner part of the Galaxy than the canonical 2.7 spectral index of the CRs observed at Earth. Consequently we obtain a higher value for the multi-TeV neutrino flux from the same Galactic plane region than previous canonical estimates. Any leptonic contribution to the multi-TeV diffuse emission will lower the actual diffuse neutrino flux. A more detailed account of this calculation may be found in [13].

Since the MILAGRO detection of the diffuse multi-TeV γ-rays from the inner Galaxy only covers the angular range $30^\circ < l < 65^\circ$ [2], in order to make the MILAGRO data point applicable to the whole inner Galaxy (with coordinates $-40^\circ < l < 40^\circ$), it was assumed that the MILAGRO TeV flux, for the rest of the region, would scale in a similar way to the EGRET GeV flux across the region.

It is worth noting that the muli-TeV energy range in which MILAGRO operated is the energy range where km^3-scale neutrino telescopes reach their best performances (see [14, 15] and Sec.). This indicates that the MILAGRO observations are the most relevant γ-ray observations to constrain the expected diffuse neutrino flux, since γ-rays and neutrinos are produced roughly at the same energy during CR hadronic interactions with the interstellar medium.

In Sec. we review the relevant γ-ray observations that constrain the expected neutrino flux from the inner Galaxy, suggesting different possibile fits to the γ-ray data in scenarios where the emission is dominated by hadronic CR interactions. In Sec. we use such fits to evaluate the expected flux of neutrinos from the inner Galaxy. Our conclusions are provided in Sec. .

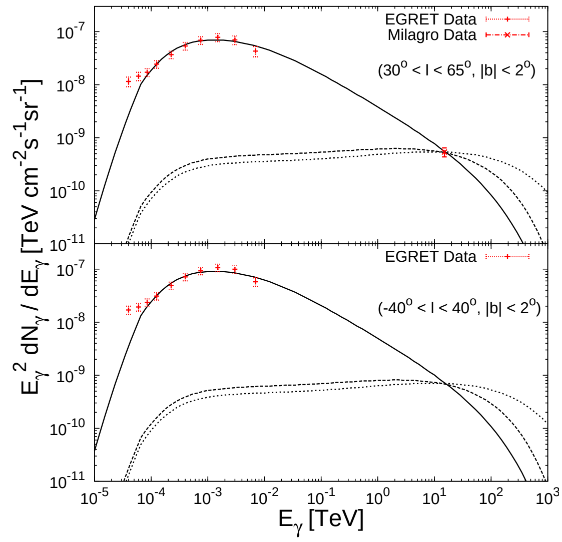

FIGURE 1. **Top panel:** EGRET and MILAGRO data points for the Galactic plane region with coordinates $30^\circ < l < 65^\circ$. The solid line represents a fit to both the sets of data due to π^0-decay γ-ray emission from the CR spectrum described by Eq. 1. The dotted and dashed lines represent the γ-ray emission from a hard ($\propto E^{-2}$) CR spectrum that fits the MILAGRO point only. **Bottom panel:** EGRET data points for the inner Galaxy ($-40^\circ < l < 40^\circ$). Lines are the same as in the top panel rescaled upwards by a factor ~ 1.3.

DIFFUSE γ-RAYS FROM THE INNER GALAXY

The MILAGRO detection of a diffuse emission from both the Cygnus region ($65^\circ < l < 85^\circ$) and the more central region of the Galaxy ($30^\circ < l < 65^\circ$), represents more than seven years worth of data collection. The detector's large field of view ($\sim$2 sr) and almost continuous data aquisition rate makes it highly suitable for discovering large-scale diffuse γ-ray signals which Air-Cherenkov instruments, with much smaller fields of view, would find more difficult to detect. The most significant of the MILAGRO diffuse flux detections originates from the Cygnus region and is 8.6 σ above the background [1]. The central Galactic region was also detected with a smaller but still very robust significance of 5.1 σ [2]. The median energy of the detected photons is in both cases 15 TeV.

As we are here interested in the emission from the inner Galaxy, we plot in Fig. 1 the available γ-ray measurement for two distinct regions of the Galactic plane. A good fit to all the γ-ray data can be obtained by assuming that the CR spectrum in the region considered here is not a single power law but rather a broken power law:

$$J(E) = J_0 \, \frac{E^{-\alpha}}{\left[1 + (\frac{E}{E_*})^\delta\right]} \, e^{(-E/E_{\rm cut})} \, , \qquad (1)$$

with slope $\alpha = 2$ and $\alpha + \delta = 2.7$ below and above $E_* =$ 80 GeV respectively. An exponential cutoff is added at an energy of $E_{\rm cut} = 1$ PeV, close to the energy of the CR knee. Here J_0 determines the total energy in the form of CRs. A physical justification of such a spectral shape has been provided in [4], where the authors suggested to interpret E_* as the energy where the escape of CRs from the Galaxy changes from convective to diffusive.

The γ-ray emission resulting from proton–proton interactions between CRs with the spectrum considered in Eq. 1 and interstellar gas has been calculated using the parameterization given in [16] and is plotted as a solid line in Fig. 1 (top panel). The curve fits both the EGRET and MILAGRO data, with the exception of the data points at energies below $\approx$ 100 MeV, where electron Bremsstrahlung is well known to be the dominant mechanism for γ-ray production in the Galactic disk [4, 17].

Alternatively, a hard CR spectrum of the form,

$$J(E) = J_0 \, E^{-2} \, e^{(-E/E_{\rm cut})} \, , \qquad (2)$$

which fits the MILAGRO point and is represented in Fig. 1 (top panel) by the dashed and dotted lines, characterized by two different values for the position of the high energy cutoff of 1 and 5 PeV respectively. This hard CR spectrum described by Eq. 2 provides a negligible contribution to the low energy ($\approx$ GeV) EGRET γ-ray detection, explained by conventional models with a steep CR spectrum [3, 17].

To estimate the diffuse neutrino flux from the inner Galaxy we proceed as follows. We call here inner Galaxy the region of galactic coordinates $-40^\circ < l < 40^\circ$ and $-2^\circ < b < 2^\circ$. This is the region for which the diffuse emission detected by EGRET shows the highest brightness (see Fig. 2a from [3]). Thus, if the emission has a hadronic origin, the neutrino flux will be enhanced within this region. The missing piece of information is the γ-ray flux from the inner Galaxy at multi-TeV energies, which is the most relevant to constrain the neutrino emission. This flux is not available since the MILAGRO observations cover only a fraction of the inner Galaxy. We assume here that the enhancement detected by MILAGRO in the region of coordinates $30^\circ < l < 65^\circ$, which partially overlaps with the region we consider, is representative for the whole inner Galaxy and that we can rescale it following the EGRET γ-ray brightness profile. In Fig. 1 (bottom panel) we show the EGRET data points for the inner Galaxy, together with the three curves adopted in the upper panel to fit the γ-ray data. All the curves have been multiplied by 1.3 in order to follow the spatial variation of the EGRET flux. This assumption is equivalent to saying that GeV and multi-TeV CRs are distributed in the inner Galaxy in the same way. It should be kept in mind that this factor (1.3) takes into account both the spatial distribution of CRs and the increase of the gas density toward the centre of the Galaxy.

NEUTRINO FLUX FROM THE INNER GALAXY

Capabilities of neutrino telescopes

As a rule of thumb, km^3–scale neutrino telescopes can detect a persistent and point–like source at a flux level of $\approx 10^{-11}\nu$ cm^{-2} s^{-1} after a few years of continuous observations. This flux is the total flux integrated above $\approx$ 1 TeV, roughly corresponding to the observed flux of the Crab nebula in γ-rays. An accurate determination of the detection rate from a Crab-like source of neutrinos is obtained by considering the telescope's effective area and the spectrum of the neutrinos received from the source. This source rate must be compared with the detection rate of the atmospheric neutrino background. All these aspects determine the optimal energy range for astrophysical neutrino detection.

As an illustrative example, we consider here a hypothetical point–like and steady source of neutrinos with differential flux:

$$J(E) = J_0 \left(\frac{E}{\mathrm{TeV}}\right)^{-\alpha} e^{(-E/E_{\mathrm{cut}})} \qquad (3)$$

with J_0 normalised such that the integrated flux above 1 TeV is 10^{-11} cm^{-2} s^{-1}. α and E_{cut} are free parameters. For the effective area we used the one provided in [18, 19, 20] for the KM3NeT detector. Being located in the northern hemisphere, this telescope will be able to observe the inner part of the Galaxy and thus is the more relevant here. In the calculations, we used a convenient fit to the effective area which reads:

$$A_{\mathrm{eff}}(E) = 10^{4.7} E^{3.4} \left(\frac{0.24}{0.24+E}\right)\left(\frac{0.31}{0.31+E}\right)\left(\frac{37}{37+E}\right) \mathrm{cm}^2$$

where E is the neutrino energy in TeV. The product between the effective area and the neutrino flux within one angular resolution element results in the expected differential detection rate by KM3NeT, and it is shown in Fig. 2. Rates are defined as the number of neutrinos detected after one year of exposure. The adopted atmospheric background assumed a zenith angle of $\sim 70^\circ$, this being the effective zenith angle of the inner Galactic region we are interested in ($-40^\circ < l < 40^\circ, -2^\circ < b < 2^\circ$).

It is evident from Fig. 2 that the prospects for km^3 size neutrino telescopes to detect such fluxes are optimal in the 10-1000 TeV energy range, where the signal flux is well above that due to atmospheric background events and the effective area grows sufficiently quickly with energy for detection to be possible, provided of course that E_{cut}, sits at sufficiently high energies (>100 TeV). Thus the best targets for neutrino telescopes are sources with a hard spectrum up to hundreds of TeV. It is for this reason that the detection of both discrete multi-TeV γ-ray sources and the diffuse emission by MILAGRO are of crucial importance for the prospects of the first high energy astrophysical neutrinos from the Galaxy, within the coming years.

Unfortunately, for diffuse sources, the spatial spread of the signal must be integrated over angle, increasing the atmospheric background flux contamination of the total signal. We next focus on this issue, considering the expected neutrino emission from the inner part of the Galactic disk.

Neutrinos from the inner Galaxy: detectability for km^3–scale detectors

The top panel of Fig. 3 shows our predictions for the diffuse flux of neutrinos expected from the inner

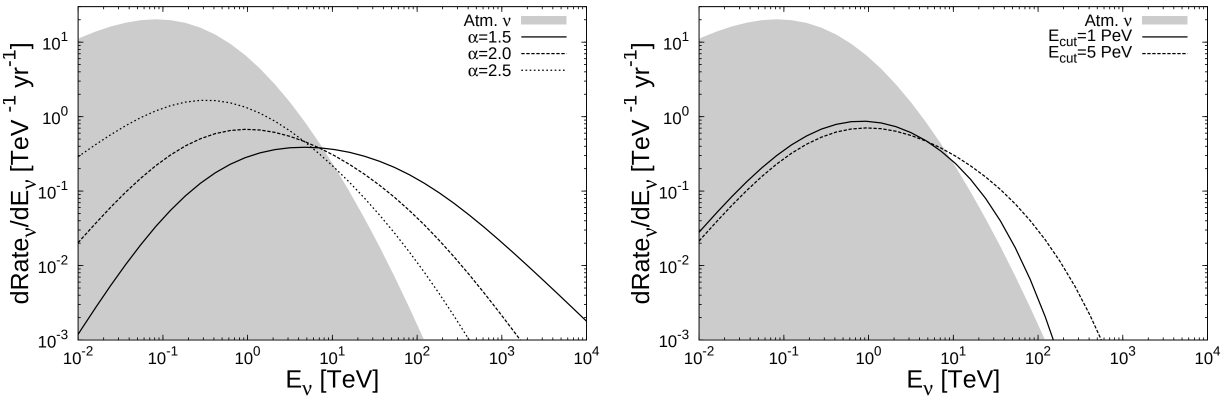

FIGURE 2. Differential detection rates for neutrino sources with flux $F(>1\ TeV) = 10^{-11}\nu\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The shaded region represents atmospheric neutrinos. **Top panel:** Solid, dashed and dotted lines represent the count rates for neutrino sources with power law spectrum with slope 1.5, 2 and 2.5 respectively and high energy cutoff at $E \gg 1$PeV. **Bottom panel:** Count rates for neutrino sources with $\propto E^{-2}$ spectra and exponential cutoff at $E_{\mathrm{cut}} = 10$ and 100 TeV (solid and dashed line respectively).

Galaxy (with coordinates $-40^\circ < l < 40^\circ, -2^\circ < b < 2^\circ$). Neutrino spectra are calculated following [16] and are the sum of all the neutrino flavours produced through charged pion decay (two muon neutrinos plus one electron neutrino) divided by three to take into account neutrino oscillations (maximal mixing). The adopted parent proton spectra are the same we used to fit the MILAGRO data (see Sec.) and then extrapolated to the whole inner Galaxy, namely, we used the same CR proton spectra that produce the γ-ray emission plotted in the bottom panel of Fig. 1.

The solid line represents the neutrinos produced by CRs with a spectrum described by the broken power law in Eq. 1, while dashed and dotted lines refer to a hard CR spectrum as in Eq. 2, with exponential cutoff at energies $E_{\mathrm{cut}} = 1$ and 5 PeV respectively. The shaded region represents the atmospheric neutrinos, integrated over the whole of the considered region, which has an extension of 0.097 steradians.

For the case of the broken power law the atmospheric neutrinos dominate over the signal for all neutrino energies. On the other hand, if a hard spectrum is considered, and the exponential cutoff in the CR spectrum is significantly above 1 PeV, the neutrinos from CR interactions in the inner Galaxy start to dominate over the atmospheric background above a few tens of TeV in energy.

To investigate the capability of a neutrino telescope to detect the diffuse emission we convolved the neutrino fluxes with the effective area, from whic we obtained the integral detection rate. The rates above a given energy E for one year of exposure are shown in the bottom panel of Fig. 3. Line types are the same as in the top panel of Fig. 3. It is evident that the detection of diffuse neutrinos from the inner Galaxy becomes most feasible for neutrino energies above a few tens of TeV, where the signal becomes comparable to or rises above the background counts rate. Above 10 TeV a rate of 5, 9 and 15 neutrinos is expected after a single year of exposure for the solid, dashed and dotted curve respectively, against a background of about 28 neutrinos per year. For the most optimistic case (dotted line in Fig. 3) the neutrino signal becomes equal to the background at an energy of 20 TeV with about 10 events per year.

The visibility of the inner Galaxy for a neutrino detector located in the Mediterranean, is $\approx 70\%$ of the year. The rates shown in Fig. 3 should be considered as the number of neutrinos after one year of exposure, ie. ≈ 1.5 yr of physical time.

DISCUSSION AND CONCLUSIONS

We have presented here our determination of the neutrino flux from the inner Galaxy, defined as the region of coordinates $-40^\circ < l < 40^\circ$ and $-2^\circ < b < 2^\circ$. Our calculations rely on the following assumptions:

1. the diffuse γ-ray emission detected at multi-TeV energies by MILAGRO from the region of the Galactic plane of coordinates $30^\circ < l < 65^\circ$ is representative for the whole inner Galaxy;
2. the diffuse galactic GeV and multi-TeV emission detected by EGRET and MILAGRO respectively follows the same spatial distribution;
3. the diffuse γ-ray emission is entirely of hadronic origin.

These assumptions allow us to obtain an almost model independent estimate for the diffuse flux of neutrinos from the inner Galaxy. Such an estimate has to be considered as the maximal expected flux of neutrinos com-

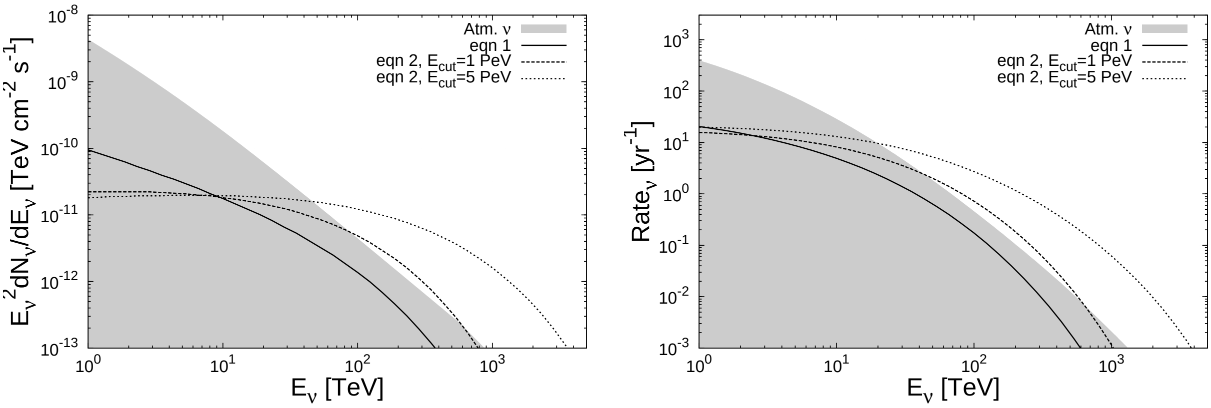

FIGURE 3. Top panel: neutrino fluxes from the inner Galaxy. Solid, dashed and dotted lines refer to an underlying CR spectrum described by Eq. 1 and Eq. 2 with $E_{\rm cut} = 1$ and 5 PeV respectively. The flux of atmospheric neutrinos is shown as a shaded region. **Bottom panel:** Detection rates integrated above an energy E in a km^3 neutrino telescope. Curves have the same meaning as in the top panel.

patible with γ-ray observations, since any leptonic contribution to the observed γ-ray emission would lower our expectations.

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