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Galactic diffuse neutrino component in the astrophysical excess measured by the IceCube experiment

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Summary. — The Galaxy is a guaranteed source of neutrinos produced by the interaction of cosmic rays (CRs) with the interstellar gas. According to conventional CR propagation models, however, this emission may be too weak to be detected even by km^3-scale neutrino telescopes. This expectation has to be revisited in the light of recent *Fermi* LAT findings showing that the CR spectrum in the inner Galactic plane is significantly harder than that inferred from local CR measurements. Here we discuss some relevant predictions of a phenomenological model —based on a spatially-dependent CR diffusion —which was recently developed to reproduce that large-scale trend. In particular, we show how that model correctly predicts the TeV γ-ray diffuse emission measured by Milagro and H.E.S.S. in the inner Galaxy. We will then compute the corresponding neutrino emission, compare it with ANTARES and IceCube results and discuss the perspectives of KM3NeT.

1. – Introduction

The IceCube experiment recently opened the era of high-energy neutrino astronomy finding a significant excess with respect to the atmospheric neutrino background (see, *e.g.*, [1-3]). While the almost isotropic distribution of the IceCube High Energy Starting Events (H.E.S.E.) points to an extra-Galactic origin of the largest part of the excess, several independent analyses claim the presence of a significant component of Galactic origin (see, *e.g.*, [4]). Strong limits on the emission of point-like sources implies that

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such Galactic component must be of diffuse nature. Although a diffuse Galactic neutrino emission is expected from the interaction of cosmic rays (CR) with the interstellar medium, conventional calculations predict a flux which is significantly lower than required to explain IceCube results [5].

Here we follow a different approach assuming a larger, and harder, CR population in the inner Galactic plane (GP) with respect to what predicted by conventional models. This is motivated by the recent *Fermi* LAT finding of an excess in the γ-ray diffuse emission from that region respect to the predictions of those models [6]. It was shown [7] as that feature can be related to a dependence of the primary CR proton spectral index on the Galactocentric radius. This behaviour was confirmed by the *Fermi* LAT Collaboration [8] as well as from an independent analysis of the same data [9]. The authors of [7] proposed a scenario in which such a behaviour is originated by a radial dependence of both the spectral index $\delta(R)$ — setting the rigidity dependence of the CR diffusion coefficient — and the advection velocity. A phenomenological model (KRA_γ) based on that scenario was shown to reproduce the *Fermi* LAT γ-ray diffuse spectrum and angular distribution over the whole sky.

In this contribution we compare the prediction of an updated version of that model (*gamma* model) with γ-ray data sets at higher energies. These will include the flux measured by Milagro at ~ 15 TeV in the inner GP [10] as well as the spectrum measured by H.E.S.S. [11] in the Galactic ridge. We will show (see also [12, 13]) that some well known (though often overlooked) discrepancies between those experimental results and the predictions of conventional models are absent for the *gamma* model. We will then use the same scenario to compute the neutrino diffuse emission of the Galaxy above the 10 TeV, showing that it is significantly larger than that computed with conventional models and compare our results with recent IceCube and ANTARES results.

2. – The *gamma* model

The KRA_γ model proposed in [7] assumes that the exponent δ, setting the rigidity dependence of the CR diffusion coefficient, has a linear dependence on the Galactocentric radius (R): $\delta(R) = AR+B$. The parameters A and B are tuned to consistently reproduce CR and γ-ray data. Assuming the mean CR source spectral index to be the same in the whole Galaxy, this behaviour turns into a radial dependence of the propagated CR spectral index hence also of the longitude dependence of the γ-ray spectrum along the GP. The model was found to reproduce the radial dependence of the CR spectral index determined by the *Fermi* LAT Collaboration [8]. The setup was implemented with `DRAGON`, a numerical code designed to compute the propagation of all CR species [14, 15] in the general framework of position-dependent diffusion.

The modified version of the model discussed here (*gamma* model) also accounts for the CR nuclei spectral hardening at $\sim 250\,\mathrm{GeV/n}$ which was inferred from Pamela [16] AMS-02 [17] data and CREAM [18]. This hardening is assumed to be present in the whole Galaxy and it is effectively implemented as a feature in the CR source term. In order to reproduce KASCADE-Grande [19] data here we adopt an exponential cut-off energy $E_{\mathrm{cut}} = 5\,\mathrm{PeV/nucleon}$ in the source spectra. Finally, a proper gas distribution has to be adopted to properly model the hadronic emission. While for $R > 1.5\,\mathrm{kpc}$ we use the same *ring model* used by the *Fermi* LAT Collaboration (see, *e.g.*, [6]), in the inner region we adopt the 3-dimensional analytical model presented in [20].

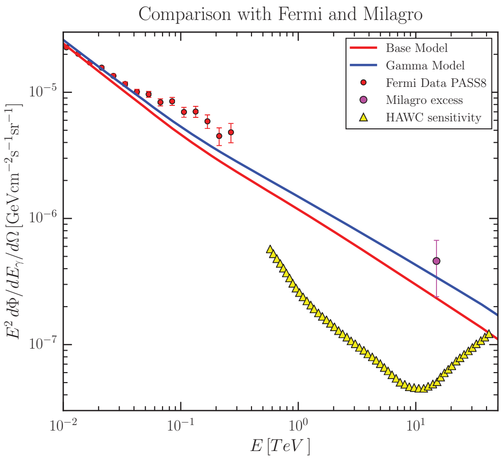

Fig. 1. – The diffuse emission γ-ray spectrum measured by *Fermi* LAT and Milagro in the inner Galactic plane ($|b| < 2°$, $30° < l < 65°$) is compared with the predictions of the *base* (conventional) and the *gamma* models. The expected sensitivity of HAWC is reported.

3. – Comparison with γ-ray data above the TeV

We start comparing the *gamma* model predictions with Milagro results. This water Cherenkov experiment measured the γ-ray flux in the sky window with $|b| < 2°$ and $30° < l < 65°$ at a median energy of 15 TeV. This was found to be 4σ above the flux computed with the (2008 state of the art) conventional model based on the GALPROP code. The excess is not explained also with more updated conventional models including the *Fermi* LAT benchmark diffuse model based on GALPROP [21]. In fig. 1 (red line) we report the prediction of a representative conventional (*base*) model which also accounts for the CR proton e Helium spectral hardening at about 250 GeV/n so to reproduce PAMELA, AMS-02 and CREAM data. In the same figure we also report *Fermi* LAT (PASS8) data extracted with the *Fermi tools*(¹). Point sources from the 3FGL catalogue were subtracted. In agreement with our previous considerations, we see that conventional models underestimate experimental results even in that energy range. In fig. 1 the reader can also see as the predictions of the *gamma* model are in a better agreement with those data than the corresponding conventional model.

We also checked the *gamma* model against H.E.S.S. and *Fermi* LAT (PASS8) data in the Galactic ridge region: $|l| < 0.8°$, $|b| < 0.3°$. Again, we subtracted point sources from the 3FGL catalogue.

The γ-ray diffuse emission from that region is expected to be dominated by the decay of π^0 produced by the interaction of the hadron component of CR with the dense molecular gas complex in the GC region (Central Molecular Zone) extending ~ 250 pc around the GC in the GP. The spectrum measured by the H.E.S.S. observatory [11] is significantly harder ($\Gamma = -2.29 \pm 0.07 \pm 0.20$) than expected assuming the CR spectral index in the GC region to be similar to the locally observed one, as assumed by conventional CR transport models.

(1) `http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/references.html`.

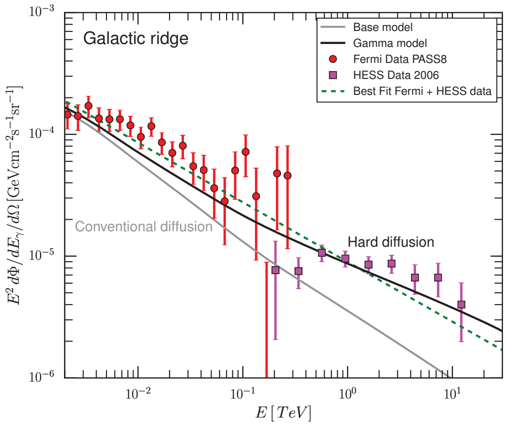

Fig. 2. – The γ-ray spectrum in the Galactic ridge region ($|l| < 0.8°$, $|b| < 0.3°$). *Fermi* LAT and H.E.S.S. data are compared with the contribution of the Galactic CR *sea* computed with the *gamma* and *base* models. The single power-law best fit of the combined data is also reported.

As show in figs. 1 and 2 both the H.E.S.S. and *Fermi* LAT data can naturally and consistently be explained by the hadronic emission originated by the Galactic CR sea if that is computed with the *gamma* model.

4. – Comparison with IceCube and ANTARES results

The hadronic γ-ray emission which we discussed in the previous sections must be accompanied by a neutrino emission with a similar spectrum. Concerning its flavor composition, neutrino oscillations over astrophysical distances are expected to equally redistribute it among the three lepton families. Even accounting for the CR spectral hardening at $\sim 250\,\mathrm{GeV}/n$, conventional computations (see, *e.g.*, [5] where the *Fermi* LAT benchmark model was adopted) predict an emission which can hardly exceed 8% of the astrophysical flux measured by IceCube [1] and it is hardly detectable even by km^3-scale neutrino telescopes.

Similarly to what done in [12] here we recompute the Galactic neutrino emission using the *gamma* model which, as we showed, provides a better description of γ-ray data in the inner GP. On the whole sky the Galactic contribution is subdominant and difficult to discriminate from an isotropic extragalactic component. A better strategy is to look for an excess in the inner GP where the Galactic component is expected to be dominant and the *gamma* and conventional models predictions are maximally different. Noticeably the ANTARES experiment, which has been taking data between 2007 and 2013 in the energy range [3–300] TeV [22] has already put interesting upper limits on the ν_μ flux in the window: $|l| < 30°$ and $|b| < 4°$.

In fig. 3 we compare the ν_μ flux multiplied by three, assuming flavour equipartition, computed with the *base* (conventional) and *gamma* setups with that experimental constraint. We notice the large enhancement (almost a factor of 5 at 100 TeV) obtained respect to the conventional scenario. Indeed, while the *base* model may hardly be detectable even by the KM3NeT observatory [23], our prediction for the *gamma* model is instead well above the sensitivity reachable by that experiment in 4 years and it is almost within the ANTARES observation capabilities. For comparison we also report the

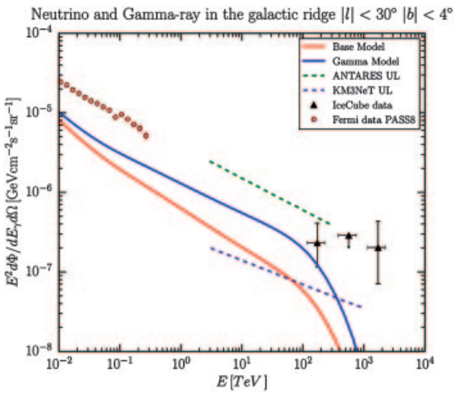

Fig. 3. – All-families neutrino spectra in the inner Galactic plane region. We also show the maximal flux, estimated considering 3 years of IceCube HESE events, the constraint from ANTARES experiment [22] as well as the deduced sensitivity of the future Mediterranean observatory KM3NeT [23] after 4 years of lifetime.

maximal flux which we inferred from the fraction of IceCube H.E.S.E. events compatible with that region. A good agreement with IceCube results is also found on the whole Galactic plane (see, *e.g.*, the right panel of fig. 1 in [24]).

5. – Conclusions

Several independent analyses of the *Fermi* LAT results agrees about the presence of a Galactocentric radial dependence of the CR spectral index. We showed that a phenomenological model which accounts for that behaviour in terms of spatial-dependent diffusion also provides a satisfactory description of, so far unexplained, Milagro and H.E.S.S. results. Independent tests of this scenario should come soon from the HAWC water Cherenkov telescope [25].

This scenario open interesting perspectives for high energy neutrino astronomy. In fact, the detection of the diffuse Galactic neutrino emission by the current generation of km^3 scale neutrino telescopes become possible under the conditions of the presented scenario, especially for detectors located in the Northern hemisphere.

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