EPJ Web of Conferences **319**, 05005 (2025) https://doi.org/10.1051/epjconf/202531905005
*RICAP-24*

# Do the LHAASO Galactic diffuse emission data require a contribution from unresolved sources?

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**Abstract.** The Large High-Altitude Air Shower Observatory (LHAASO) collaboration has recently measured the ultra-high energy gamma-ray diffuse emission ($10 - 10^3$ TeV) after masking the contribution of known sources. The observed signal appears to be $2 - 3$ times higher than expected from the hadronic interactions of diffuse cosmic rays with the interstellar medium, potentially suggesting a contribution from unresolved sources. However, estimates of the diffuse emission are affected by large uncertainties. In this work, we calculate the hadronic gamma-ray diffuse emission, accounting for uncertainties in the gas content of the Galactic disk, the energy and spatial distribution of cosmic rays, and the hadronic interaction cross-section. We show that the LHAASO data above $\sim 30$ TeV are consistent with this model, not requiring (nor probing) the existence of any further contribution due to unresolved sources or cosmic ray spectral variations in the inner Galaxy.

## 1 Introduction

The study of gamma-ray emission produced by cosmic rays (CRs) interacting with the interstellar medium (ISM) after escaping the accelerator environment is crucial for understanding cosmic-ray origin and propagation. Recently, the LHAASO collaboration reported a measurement of the diffuse Galactic gamma-ray emission at $10 - 10^3$ TeV in two sky regions using the data recorded by the square kilometer array (KM2A) [1], masking known TeV sources included in the TeVCat and the LHAASO KM2A catalog [2]. The observed flux exceeds theoretical predictions for CR diffuse emission by a factor of 3 (2) in the inner (outer) regions of the Galaxy. According to [3], theoretical models cannot fully explain the combined *Fermi*-LAT and LHAASO data from several GeV and up to $\sim 60$ TeV. It was suggested that the observed excess might result from unresolved sources [4–7].

In this work, we model the total diffuse emission and compare it with LHAASO data (see [8] for more details). We calculate the emission produced by the interaction of CRs with the ISM accounting for uncertainties in the CR spectrum, the $pp$ cross-section, and the Galactic gas distribution. We also explore whether the spatial dependence of the CR spectral index, i.e., CR spectral hardening, inferred from the analysis of the large-scale diffuse emission with *Fermi*-LAT at 20 GeV [9–11], extends to the energy range $> 10$ TeV probed by LHAASO.

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## 2 Method

The interaction with the ISM of accelerated protons and heavier nuclei propagated in the Galactic magnetic field results in high energy gamma-ray diffuse emission. Providing a theoretical estimate of this component is of fundamental importance to interpret the data and requires a careful treatment of all the involved uncertainties.

The gamma-ray diffuse emission as a function of the photon energy, $E_\gamma$, and arrival direction, $\hat{n}_\gamma$, is parametrized in the following way [12, 13]:

$$\varphi_{\gamma,\mathrm{diff}}(E_\gamma, \hat{n}_\gamma) = \int_{E_\gamma}^{\infty} dE \, \frac{d\sigma(E, E_\gamma)}{dE_\gamma} \times \int_0^{\infty} dl \, \varphi_{\mathrm{CR}}(E, \mathbf{r}_\odot + l\hat{n}_\gamma) \, n_{\mathrm{H}}(\mathbf{r}_\odot + l\hat{n}_\gamma) e^{-\tau(E_\gamma, l\hat{n}_\gamma)}, \quad (1)$$

where $\frac{d\sigma(E,E_\gamma)}{dE_\gamma}$ is the differential cross section for the photon production as a function of the CR energy $E$; $\varphi_{\mathrm{CR}}(E, \mathbf{r})$ is the CR flux as a function of energy and position in the Galaxy, $\mathbf{r}$, where $\mathbf{r} = \mathbf{r}_\odot + l\hat{n}_\gamma$ with $\mathbf{r}_\odot = 8.5$ kpc the position of the Sun with respect to the Galactic center and $l$ the length of the line of sight. Finally, $n_{\mathrm{H}}(\mathbf{r})$ is the number density of target nucleons, while the exponential function takes into account the photon absorption in the interstellar radiation field (mainly due to the Cosmic Microwave Background radiation) which suppresses the flux produced at large distances [14]. The integral is performed over the nucleon energy $E$ and along the line of sight $l$.

The modeling of the diffuse emission is subject to significant uncertainties that must be considered [15]. In this work, we adopt a fiducial model for the diffuse gamma-ray emission and we estimate the variations due to theoretical and observational uncertainties. Our fiducial model uses AAFRAG for the cross-section [16], the GALPROP gas maps for the gas templates [17], Dembinski et al, 2017 [18] for the CR spectrum, the CR spatial distribution from Cataldo et al, 2019 [13], and assumes standard diffusion without hardening. Significant uncertainties arise from varying the above-mentioned model parameters. For the cross-section, we also use the SYBILL-based parametrization from [19]. Gas template uncertainties are addressed using also the hydrogen column density ($N_H$) traced by the PLANCK dust opacity ($\tau_D$) map obtained at 353 GHz (http://www.esa.int/Planck). While, in order to account for the observational uncertainty in the proton spectrum, we consider an alternative fit matching KASKADE data while keeping heavier nuclei unchanged [8]. The effect of the CR spectral hardening is discussed separately and implemented following [12, 13].

## 3 Results

**Diffuse emission.** Fig. 1 shows our results for the Galactic gamma-ray diffuse emission in the inner (left panel) and outer (right panel) regions observed by LHAASO, compared with the corresponding experimental data. The dashed black line shows the predictions of our fiducial model. For both regions, we have applied the mask adopted by LHAASO. The cyan, green, and blue shaded bands show the deviations from the fiducial model produced by variations of the assumed $pp$ cross-section, CR spectrum, and gas template, respectively. The right panel in Fig. 1 shows that our fiducial model is compatible with LHAASO data in the outer region and that the relatively small discrepancies can be easily accommodated within the uncertainty ranges. In the inner region (left panel), our calculations are still consistent with experimental data above ∼ 30 TeV, without requiring a CR spectral hardening in the inner Galaxy and/or a significant contribution from unresolved sources. However, the first two data points, below 30 TeV, are marginally above expectations, even after accounting for all the uncertainties, suggesting that a possible additional contribution from unresolved sources could indeed be relevant in this energy band. The above conclusions are then different from those put forward by the LHAASO collaboration [1], according to which the measured fluxes exceed the theoretical expectation by a factor $\sim 2-3$. We note, however, that the theoretical model used in that work accounted only for uncertainties in the CR spectrum, while their assumptions for the cross section (AAFRAG) and gas distribution (derived from the dust) both tend to minimize the diffuse flux. For reference, we reported the theoretical predictions used by the LHAASO collaboration as an orange band in Fig. 1 [see Fig. 2, 1].

**Hardening of the CR spectrum.** We test the effects of a progressive hardening of the CR spectrum toward the Galactic center to understand whether such a scenario can be constrained by LHAASO data. The outer region ($125° < l < 250°$) is not affected by this possibility, due to its distance from the hardening zone identified by *Fermi*-LAT. Consequently, we only evaluate the impact of the hardening in the inner region, where it can produce a sizable enhancement of the emission. However, also in this region, the LHAASO 's almost total masking of $l \leq 80°$ and $|b| < 1°$ significantly reduces this effect by filtering out the contribution of most relevant Galactic regions.

In Fig. 2, we show the enhancement of the diffuse gamma-ray emission in the inner region resulting from the CR spectral hardening, compared to our fiducial case. The black and green lines are obtained with and without applying the LHAASO mask, respectively. The enhancement factor is independent of the adopted cross-section, gas template, and CR spectrum. It depends, however, on the assumed CR spatial distribution, as it can be appreciated by comparing results obtained with $g(\mathbf{r}) = g_{\rm snr}(\mathbf{r})$ (see [8, 13]) and $g(\mathbf{r}) = 1$. The effect produced by the hardening is larger in the first case because this corresponds to concentrating more CRs in the central region of the Galaxy (where CR sources are more abundant) rather than at its edges. Even in this most favorable case ($g_{\rm snr}(\mathbf{r})$), the enhancement is significantly suppressed once the mask is applied, decreasing to 16% (28%) at 10 TeV (500 TeV) (see black solid line). In conclusion, the effect of CR hardening is reduced by the masking procedure to a level comparable to or smaller than the other uncertainties associated with the diffuse emission, making it difficult to draw firm conclusions based solely on comparing theoretical predictions with LHAASO data.

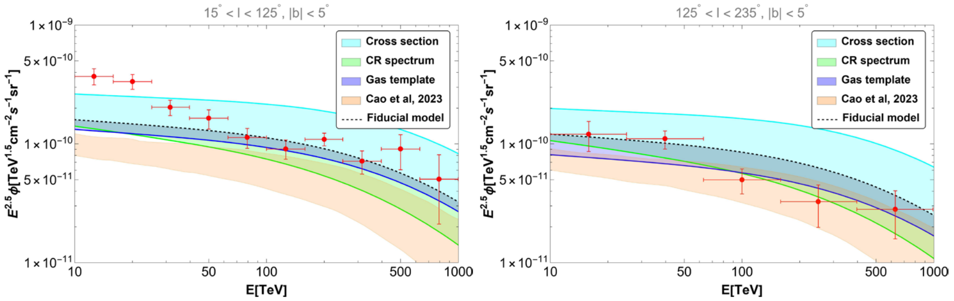

**Figure 1.** Differential energy spectra of diffuse $\gamma$−rays from the Galactic plane in the two angular regions probed by the LHAASO detector. Red data points are the measurements provided by LHAASO [1]. The dashed black line represents our fiducial model for the diffuse emission. The cyan, green, and blue shaded bands represent the variation with respect to the fiducial model related to a change of the cross-section, the CR spectrum, and the gas template assumptions, respectively. The orange band represents the theoretical predictions used by the LHAASO collaboration [1].

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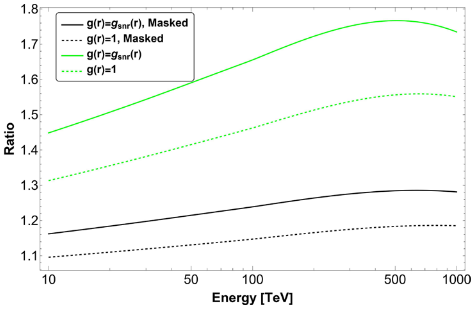

**Figure 2.** Ratio, in the inner LHAASO region, between the total diffuse emission computed including the galactic center hardening and that computed in our fiducial case. Green and black lines refer to the flux before and after applying the LHAASO masks, while the dashed and solid lines identify the cases with spatially uniform and non-uniform CRs respectively.

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