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SEARCH FOR 100 TeV γ-RAY EMISSION FROM THE GALACTIC DISK

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ABSTRACT

A search for UHE (≥ 100 TeV) diffuse γ-ray emission from the Galactic disk has been carried out, through the excess in the cosmic-ray counting rate, by means of the EAS-TOP extensive air shower array at the Gran Sasso Laboratories. Measurements are performed from angular scales $|b| \approx 2°$ (as in 100 MeV satellite experiments, and as expected from CR interactions with the ISM) to $|b| \approx 10°$. The obtained upper limits (90% c.l.) to the γ-ray excess over the cosmic-ray flux from the Galactic disk region are $I_\gamma/I_p < 0.2\%$ for $|b| < 2°$, $I_\gamma/I_p < 0.04\%$ for $|b| < 5°$, and $I_\gamma/I_p < 0.02\%$ for $|b| < 12°$ at $E_0 > 130$ TeV, corresponding to upper limits to the flux of $I_\gamma < 3.2 \times 10^{-13}$ cm^{-2} s^{-1} rad^{-1}, $I_\gamma < 2.8 \times 10^{-13}$cm^{-2} s^{-1} rad^{-1}, and $I_\gamma < 4 \times 10^{-13}$ cm^{-2} s^{-1} rad^{-1}.

Subject headings: cosmic rays — gamma rays: observations

1. INTRODUCTION

The disk of our Galaxy was the first object to be established as a source of ≥ 10 MeV gamma rays, first by means of *OSO 3* (Kraushaar et al. 1972) and then by the *SAS 2* (Hartman et al. 1979) and *COS-B* (Mayer-Hasselwander et al. 1982) satellite experiments (up to the GeV region). The main features of such emission consists in a general concentration of the flux in a narrow band around the disk ($|b| < 2°$, the flux being $I(> 100$ MeV$) \approx 3 \times 10^{-5}$ cm^{-2} s^{-1} rad^{-1}), with an enhancement toward the Galactic center by a factor ≈ 2.

The emission from the Galactic plane is essentially due to diffuse radiation, produced by the interactions of cosmic rays (CR) with the interstellar matter (ISM) and photons. The contribution from the CR electron component (mainly through bremsstrahlung and inverse Compton radiation) is expected to dominate at $E_\gamma < 100$ MeV, while the principal γ-ray production mechanism at $E_\gamma \geq 100$ MeV is thought to be decay of π^0 produced in the collisions of the CR nucleon component with the particles of the ISM (e.g.: $p + p \rightarrow \pi^0 + X$). A study of the γ-ray spectrum, extended into the VHE ($\approx$TeV) and UHE ($\approx$100 TeV) regions is a powerful tool to obtain information on the local HE cosmic-ray spectrum in different regions of the disk (and it indeed appears to depend on Galactic longitude in the GeV energy range [Bloemen 1987]). The expected ratio between the γ-ray flux I_γ and the CR flux I_p is $I_\gamma/I_p = 6.4 \times 10^{-5}$, the integral flux I_γ being $I_\gamma(> 100$ TeV$) \approx 6.6 \times 10^{13}$ cm^{-2} s^{-1} sr^{-1} (Berezinsky & Kudryavtsev 1990), coming from a region of linear dimensions $\approx$100 pc around the Galactic plane (i.e., $|b| < 1°$, consistent with the satellite data).

The Galactic γ-ray spectrum could be harder than the local cosmic-ray one, if γ-rays were produced by cosmic rays near the acceleration region and hence with a flatter spectrum (and it is surprising that the extrapolation of the 100 MeV data with power index of energy spectrum $\gamma_d = 2.1$ fits fairly well the CR anisotropy observed at primary energies $E \approx 10^{13}$ eV [Alexeenko & Navarra 1985]), and in such case the value of $I_\gamma(> 100$ TeV) would be larger than the quoted one.

The investigation of the UHE γ-ray flux from the Galactic plane is also interesting in view of the possibility of UHE γ-ray production through the decay of relic superheavy (up to 10^8 GeV) particles (Ellis et al. 1990; Berezinsky 1990, 1991) weakly interacting with ordinary matter. If these particles in our Galaxy have a distribution peaked toward the Galactic center and the Galactic plane, then the produced γ-rays must follow this distribution. The measurement of the UHE γ-ray flux from the Galactic plane could then be a useful tool to achieve upper limits to the density of such particles.

At primary energies $E_\gamma > 100$ GeV, only indirect measurements are possible, and these are performed by means of ground-based observations of the cascades produced by γ-ray primaries in the atmosphere, i.e., by means of atmospheric Cherenkov detectors in the energy range 100 GeV $\leq E_\gamma \leq 10$ TeV, and extensive air showers (EAS) arrays at $E_\gamma > 30$ TeV. The sensitivities of such techniques are limited by the proton- and nucleon-induced showers background.

First positive results on the diffuse Galactic emission in the TeV energy range obtained by means of the atmospheric Cherenkov technique (Fomin, Vladimirsky, & Stepanian 1977; Weekes, Helmken, & L'Heureux 1979; Dowthwaite et al. 1985) have, however, not been confirmed by further measurements (Reynolds et al. 1990).

At higher energies ($E_\gamma > 30$ TeV), a few measurements have been carried out by means of the EAS technique, and all the results obtained until now, with or without rejection criteria of

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nuclear primaries, have provided upper limits (Lambert, Lloyd-Evans, & Watson 1983; Clay, Protheroe, & Gerhardy 1984; Morello et al. 1987; Matthews et al. 1991) to the γ-ray flux inside angular windows $|b| < 10^\circ$.

In the following we will present the results of a search for excesses in the cosmic-ray counting rate from the region of the Galactic disk, performed with the EAS-TOP extensive air shower array, from the angular scales compatible with the satellite data, and expected from the distribution of ISM ($|b| < 2^\circ$), up to $|b| \approx 10^\circ$.

2. THE ARRAY

The EAS-TOP array (Aglietta et al. 1986, 1988) (in operation since the beginning of 1989) is located at Campo Imperatore (2005 m above sea level, 42°27′N, longitude 13°34′E, above the underground Gran Sasso Laboratories). The array (see Fig. 1) includes the following:

1. The detector of the electromagnetic component of extensive air showers, consisting of 29 modules of scintillation counters, 10 m^2 each, separated by 17 m in the compact part of the array and by 80 m at the edges, thus covering an area of $\approx 10^5$ m^2. The scintillators (16 per module) are equipped with two photomultipliers operating in high gain mode for timing measurements and low gain mode for particle density measurements. The array is organized in 10 subarrays of seven (or six) modules each and two subarrays of four modules, interconnected with each other. Each subarray operates in an independent mode: the trigger is provided by any coincidence of four adjacent modules (threshold ≈ 0.3 particles per module) within any subarray. The trigger rate is ≈ 35 Hz and the energy threshold is $\approx 5 \times 10^{13}$ eV. The absolute arrival time of the events is measured with a precision of 100 μs through a rubidium clock synchronized with the standard time provided by the Italian national broadcasting company.

2. A 12×12 m^2 detector (Aglietta et al. 1991a) of the muonic ($E_\mu > 2$ GeV) and hadronic ($E_h > 50$ GeV) components of EAS consisting of nine active layers (streamer tubes for muon tracking and proportional tubes for hadron calorimetry) interleaved with a 13 cm thick iron absorber.

3. A detector of atmospheric Cherenkov light (Aglietta et al. 1989) consisting of eight stations equipped with imaging devices, to extend the measurements into the TeV region.

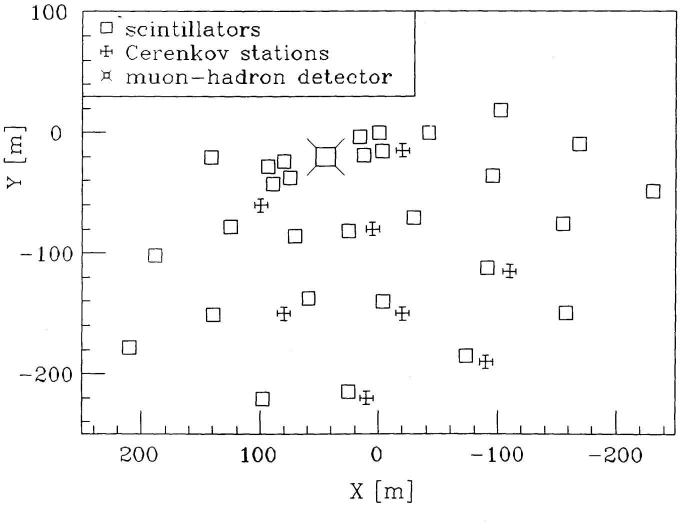

FIG. 1.—General layout of the EAS-TOP array

Pieces of equipment (2) and (3) will be operational in 1992; in the forthcoming analysis, a data base of ~2 yr (1989–1990) from the EM detector (1) has been used (preliminary results have been presented in Aglietta et al. 1991b, c).

3. DATA ANALYSIS AND ANGULAR RESOLUTION

The collected events are divided in two classes: (1) S_1 (frequency $\nu \approx 1.5$ Hz, $E_{\rm eff} \approx 130$ TeV—see the Appendix for the definition of effective energy): at least one complete subarray (six or seven detectors) has been triggered and the maximum number of particles has been detected by an inner module, which is expected to be the closest to the shower core, i.e., the core is confined with the array; (2) S_2 (frequency $\nu \approx 25$ Hz, $E_{\rm median} \approx 80$ TeV): less than six-(seven-)fold coincidences or events with the core outside the array.

For all events, the arrival directions are obtained from the time of flight technique by fitting a plane to the shower front: for S_1 events, since we use only the timing measurements performed by the detectors surrounding the core (having recorded similar number of particles at similar core distances); for S_2 events, because, due to the lack of core location, it is not possible to take into account the effect of the shower front curvature.

The angular resolution, the absolute pointing accuracy, and its stability in time are among the main features of the array and are continuously checked. Different approaches are followed:

1. Internal coherence of data, which is tested through the comparison of the two different arrival directions measured by two subsets of a subarray (three detectors each). If σ_ψ is the width of the difference distribution $\sigma_\alpha = \sigma_\psi/2$ is the arrival direction error when all the detectors of the array are used. For S_1 events on the whole, the angular resolution $\sigma_{\alpha 1}$ is $\approx 0\overset{\circ}{.}8$, while for S_2 events $\sigma_{\alpha 2} \approx 1\overset{\circ}{.}6$ ($2\overset{\circ}{.}5$ taking into account the indetermination due to the lack of core location).

2. Comparison of the EAS measured arrival directions with those of the high energy (TeV) muons recorded by the tracking systems of the detectors located in the underground laboratories (whose muon energy threshold at the surface is $E_{\rm th} =$ 1.4 TeV and the angular resolution, due to the muon scattering in the rock, is $\Delta\theta < 0\overset{\circ}{.}6$). First results (Bellotti et al. 1990), obtained in coincidence with the MACRO detector, give for the average values and widths of the two projections of such differences $\Delta\theta_x = 0\overset{\circ}{.}04 \pm 0\overset{\circ}{.}10$ and $\Delta\theta_y = -0\overset{\circ}{.}20 \pm 0\overset{\circ}{.}12$, and rms, respectively, $1\overset{\circ}{.}0$ and $1\overset{\circ}{.}2$. Such widths are thus compatible with both detector resolutions and with no systematic effect at a level of $0\overset{\circ}{.}1$–$0\overset{\circ}{.}2$.

3. Study of the shadowing effect of the Sun and the Moon on primary cosmic rays. This approach, different from (1) and (2), provides an absolute measurement of the angular resolution. Concerning S_1 events, from 10 months of data analysis, the observed deficit has a significance of 2.7 σ, and the obtained angular resolution is $0\overset{\circ}{.}83 \pm 0\overset{\circ}{.}10$ (Aglietta et al. 1991d), including systematic errors, thus confirming the result of method (1).

The search for a possible γ-ray emission from the Galactic plane on different angular scales can then be performed by means of the two independent classes of events S_1 and S_2. For both kinds of events the two observable branches of the Galactic plane (A: $40^\circ < l < 111^\circ$, toward the Galactic center—the Galactic center is not observable at the EAS-TOP latitude; B: $134^\circ < l < 205^\circ$, toward the anticenter) are divided into 19 (7) longitude intervals for S_1 (S_2) events; each interval consists of a region, rectangular in α and δ, centered on the disk (ON) of dimensions $\Delta\delta_1 = \pm 1\overset{\circ}{.}5$ for S_1 events, $\Delta\delta_2 = \pm 4^\circ$ for S_2 events and $\Delta\alpha_{1,2} = \pm\Delta\delta_{1,2}/\cos\delta$ (the values of $\Delta\alpha$ and $\Delta\delta$ are optimized in order to have the best signal-to-noise ratio). The background is evaluated by means of the number of events counted in six OFF cells similar to the ON one but shifted in right ascension of $\pm 2K\,\Delta\alpha(K = 1, 3)$. Only events with zenith angle $\theta < 40^\circ$ are used.

4. RESULTS AND DISCUSSION

The results presented in the following refer to 312 days of measurement between 1989 February and 1990 December.

The distributions in the number of counts across the Galactic disk, obtained by integrating over all the visible Galactic longitudes for the two trigger conditions and the two branches of the Galactic disk A and B are respectively shown in Figures $2a_1$, $2b_1$ (S_1 events) and Figures $2a_2$, $2b_2$ (S_2 events), and in Table 1.

A possible emission from the individual regions of the Galactic disk is searched by comparing the number of counts from the ON cell with the average number of counts (⟨OFF⟩) from the four OFF cells in the same longitude interval and shifted by $\pm 2K\,\Delta\alpha(K = 2, 3)$. The excesses in the number of counts (ON − ⟨OFF⟩)/⟨OFF⟩ from the Galactic plane as a function of Galactic longitude for the two triggers (and therefore for the two angular dimensions) are shown in Figures 3*a* and 3*b*.

TABLE 1

DISTRIBUTION OF COUNTS

Events Type	ON[a]	⟨OFF⟩[b]	ON − ⟨OFF⟩[c]	$\sigma^{d}_{on-\langle off\rangle}$
S_1 events	833,644	834,723	− 1079	1021.5
S_2 events:				
$\lvert b\rvert < 5^\circ$	29,742,510	29,748,572	− 6062	6098
$\lvert b\rvert < 12^\circ$	89,245,600	89,245,716	− 116	12,497.2

[a] Number of counts from ON cells.

[b] Average number of counts from OFF cells integrated on all visible Galactic longitudes for every angular window.

[c] Corresponding excesses.

[d] Standard deviation.

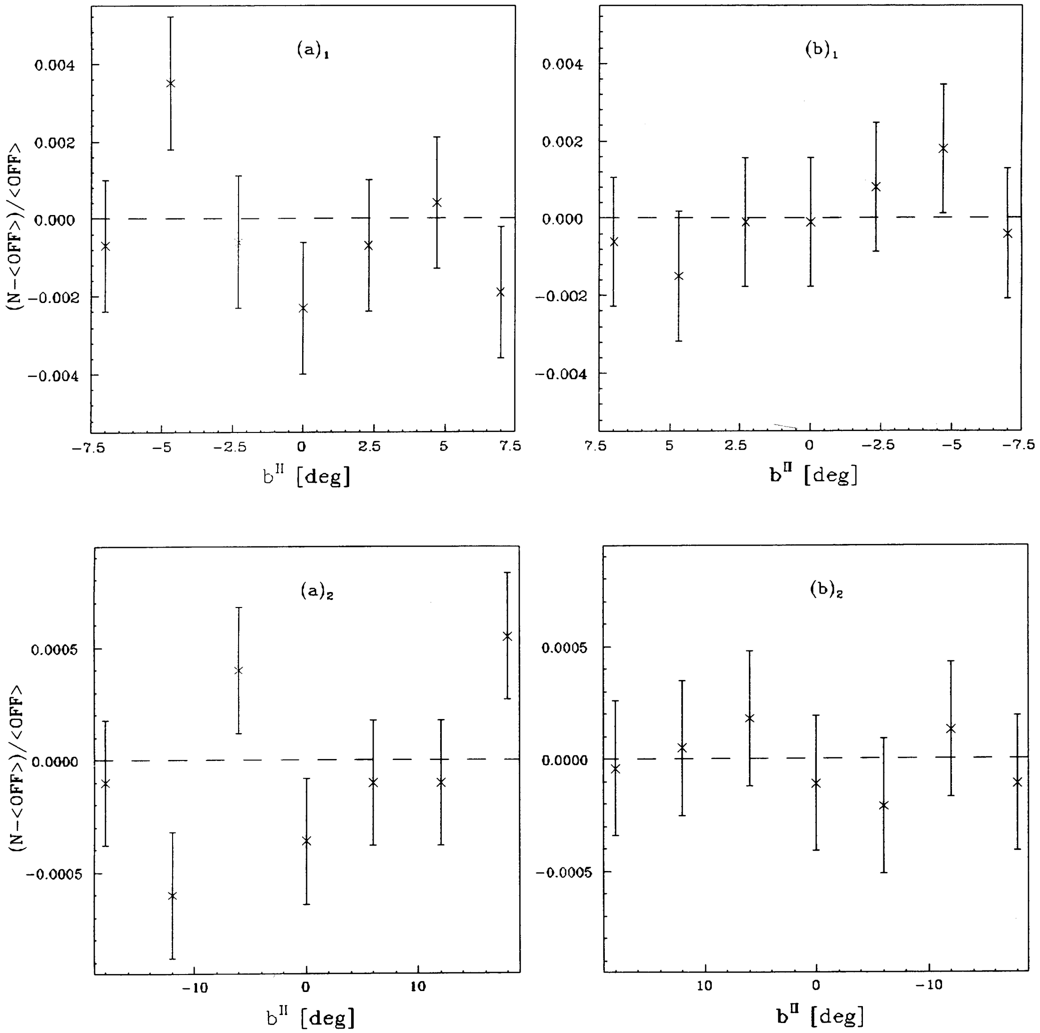

FIG. 2.—Distribution of the number of counts across the two observed branches of one Galactic disk (Figs. a_1 and b_1 refer to branches A and B, respectively, for the two classes of events S_i; see text for the definitions of A and B).

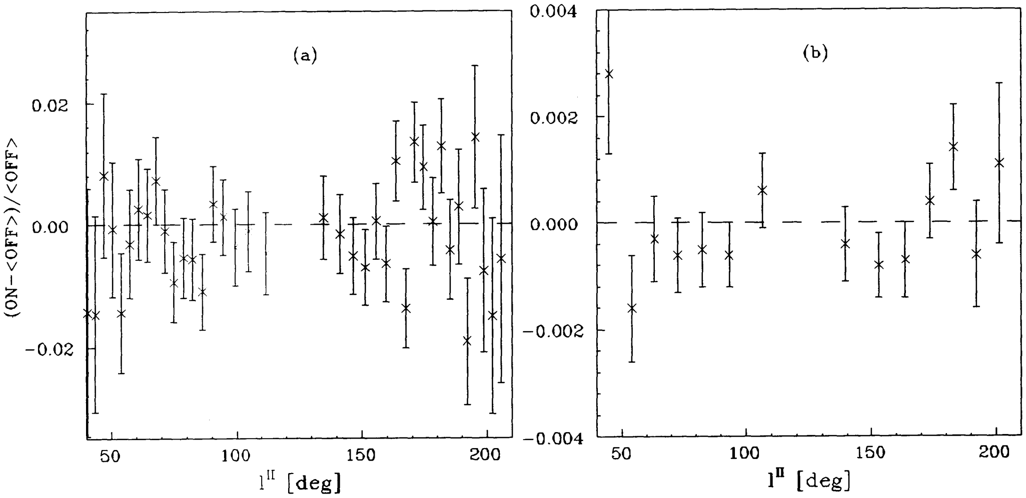

FIG. 3.—Excesses in the number of counts from the Galactic disk vs. Galactic longitude: (*a*): events S_1, $|b| < 2°$; (*b*): events S_2, $|b| < 5°$

No significant feature is observed from any longitude (a 2 σ deficit for $70° < l < 90°$ has to be studied with better statistics). The 90% confidence level upper limits derived for the two trigger conditions are for each cell (see the Appendix):

$$S_1\colon I_{A,B}(>130\ \text{TeV}) < 1.6 \times 10^{-12}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad |b_{\max}| < 2°$$

$$S_2\colon I_{A,B}(>130\ \text{TeV}) < 9 \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad |b_{\max}| < 5°$$

and, for the disk as a whole,

$$S_1\colon I_\gamma(>130\ \text{TeV}) < 3.2 \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad |b_{\max}| < 2°$$

$$S_2\colon I_\gamma(>130\ \text{TeV}) < 2.8 \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad |b_{\max}| < 5°$$

$$S_2\colon I_\gamma(>130\ \text{TeV}) < 4 \times 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad |b_{\max}| < 12°$$

The obtained upper limits to the excess in the counting rate from the Galactic plane as a whole are $I_\gamma/I_p < 0.2\%$ for $|b| < 2°$, $I_\gamma/I_p < 0.04\%$ for $|b| < 5°$ and $I_\gamma/I_p < 0.02\%$ for $|b| < 12°$.

5. CONCLUSIONS

Upper limits have been obtained to the diffuse γ-ray emission from the Galactic disk.

The limits $I_\gamma/I_p < 0.2\%$, i.e., $I_\gamma(>130\ \text{TeV}) < 3.2 \times 10^{-13}$ cm^{-2} s^{-1} rad^{-1} provide the first measurement obtained inside the angular window corresponding to the distribution of the ISM. It is still, however, a factor $\approx$30 higher than the flux calculated from the CR interactions by Berezinsky & Kudryavtsev (1990). An upper limit $I_\gamma/I_p < 0.008\%$ at $E_0 \approx 200$ TeV has recently been reported by Matthews et al. (1991) by using the μ-poor selection criteria, but inside a region around the Galactic plane $|b| < 10°$.

The lower limit that we obtain to the power-law index of the differential energy spectrum of Galactic γ-rays from 100 MeV to 100 TeV is $\gamma > 2.3$, thus setting a limit to the possibility of a hard extrapolation of the Galactic γ-ray spectrum to the 100 TeV region.

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APPENDIX

The formalism used for the calculation of the upper limits is the following:

1. S_1 events: since the effective area is known (obtained by means of a Monte Carlo simulation), the direct formulae are used:

$$I_\gamma(>E_0) < \frac{N_\gamma}{\epsilon A_{\text{eff}}\, T_{\text{eff}}(\Delta l^{\text{II}}/n)}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad \text{for the whole Galactic disk}$$

$$I_\gamma(>E_0) < \frac{n_{\gamma i}}{\epsilon_i\, A_{\text{eff}}(T_{\text{eff}}/n)(\Delta l^{\text{II}}/n)}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{rad}^{-1} \qquad \text{for each region ,}$$

where A_{eff} = effective area $\approx 3.4 \times 10^8$ cm^2, T_{eff} = total exposure time = 1.5×10^8 s, ϵ = angular efficiency = 0.67 for an emission from a region of dimensions $|b| < 1°$ (Berezinsky & Kudryavtsev 1990) ($\epsilon_i = 0.56$ for individual region), n = number of observed regions in longitude on the Galactic disk = 38, Δl = interval of observed Galactic longitude = 2.4 rad, $N_\gamma = 1.282\ \sigma_{\text{ON-OFF}}$ = number of counts ($n_{\gamma i}$ for a single region) corresponding to a 90% confidence level, and E_0 = effective energy = 130 TeV.

2. S_2 events: from the upper limit to the excess (N_γ/N_b and $n_{\gamma i}/n_{bi}$) over CR background, the following formulae are used:

$$I_\gamma(>E_0) < \frac{N_\gamma \Omega B}{\epsilon N_b(\Delta l^{\mathrm{II}}/n)} E_0^{-\gamma+1}\ \mathrm{cm^{-2}\ s^{-1}\ rad^{-1}} \qquad \text{for the whole Galactic disk}$$

$$I_\gamma(>E_0) < \frac{n_{\gamma i} \Omega B}{\epsilon_i\, n_{bi}(\Delta l^{\mathrm{II}}/n)} E_0^{-\gamma+1}\ \mathrm{cm^{-2}\ s^{-1}\ rad^{-1}} \qquad \text{for each region ,}$$

where Ω = solid angle = 1.9×10^{-2} sr, n = number of observed regions in longitude on the Galactic disk = 14, Δl = interval of observed Galactic longitude = 2.36 rad, $N_\gamma = 1.282\ \sigma$ = number of counts ($n_{\gamma i}$ is referred to a single region), N_b = number of background counts (n_{bi} for a single region), $\gamma = 2.7$ and B such that $BE_0^{-1.7} = 10^{-8}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$ at $E_0 = 100$ TeV. Using S_2 events, a further limit is given to a hypothetical more extended source, by grouping together the events counted in the three inmost cells around the Galactic plane.

The quoted energy E_0 (i.e., 130 TeV) is the effective energy E_{eff} of events S_1; the upper limits are calculated at the same primary energy also for events S_2, having assumed for γ-rays the same spectrum as for cosmic rays (the energy distributions of events S_1 and S_2 are indeed rather similar).

Concerning the upper limits I_γ/I_p, these are in any case calculated as $I_\gamma/I_p < N_\gamma/\epsilon N_p$ being thus independent from the energy spectrum or the energy threshold.

Due to the geometry used in the analysis (optimized to have a simple and fast method for the measurement of the CR background without systematic errors for each region), the angular window $|b_{\max}|$ around the disk is not strictly constant. Therefore the thickness within which the upper limits to the flux are given is, conservatively, the largest value $|b_{\max}|$, over all the observed regions.

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