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Limits on the TeV flux of diffuse gamma rays as measured with the HEGRA air shower array

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Abstract. Using data from the HEGRA air shower array upper limits on the ratio I_γ/I_{CR} of the diffuse photon flux I_γ to the hadronic cosmic ray flux I_{CR} are determined for the energy region 20 TeV to 100 TeV. A method which is sensitive only to the non-isotropic component of the diffuse photon flux yields an upper limit of $I_\gamma/I_{CR}\ (\mathrm{at\ 54\ TeV}) < 2.0 \times 10^{-3}$ (at the 90% confidence level) for a sky region near the inner galaxy ($20^\circ <$ galactic longitude $< 60^\circ$ and $|$galactic latitude$| < 5^\circ$). A method which is sensitive to both the isotropic and the non-isotropic component yields global upper limits of $I_\gamma/I_{CR}\ (\mathrm{at\ 53\ TeV}) < 1.4 \times 10^{-2}$ and $I_\gamma/I_{CR}\ (\mathrm{at\ 31\ TeV}) < 1.2 \times 10^{-2}$ (at 90% c.l.).

1 Introduction

Direct evidence for a diffuse photon radiation has sofar been obtained in a wide energy range, from the radio band up to gamma energies of ~ 50 GeV. Because of the low fluxes and the restricted sensitivity of the experiments only upper limits were reported sofar for energies above ~ 50 GeV.

In the 20 TeV to 100 TeV energy range an extragalactic component of the diffuse photon flux is expected as a result of the cascading of ultra-high-energy photons and electrons on the Cosmic Microwave Background. The estimated flux is $\sim 10^{-5}$ of the cosmic ray flux (Sigl, 1996).

Especially at low Galactic latitudes and near the Galactic center a strong Galactic component is expected, with fluxes in the order $\sim 10^{-4}$ of the cosmic ray flux (Porter and Protheroe, 1999). The dominant production mechanisms are π^0 production by hadronic cosmic rays on the interstellar matter, inverse Compton scattering of electrons on the interstellar radiation field and high-energy electron bremsstrahlung.

In this paper a new measurement of an upper limit of the diffuse photon flux is presented for the energy region from 20 TeV to 100 TeV (Denninghoff, 2001).

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2 The experiment

The data were taken with the HEGRA air shower array located at 2200 m a.s.l. on the Canary island La Palma. Since April 1998 the array consisted of 97 wide-angle Cherenkov detectors (AIROBICC) and of 182 scintillation detectors. A fire in October 1997 had destroyed 39 AIROBICC and 65 scintillation detectors, of which all 39 AIROBICC and 4 scintillation detectors were rebuilt. The data used in this analysis were taken from April 1998 to March 2000, corresponding to an on-time of ~1464 hours.

For each shower the total number N_s of photons and electrons at the detector level was determined from the scintillator data. The arrival times of the Cherenkov photons were used to reconstruct the shower direction. In addition, the data from the Cherenkov detectors allowed the determination of the position of the shower core and of the Cherenkov light density $\rho(r)$ as a function of the distance r from the shower core. From $\rho(r)$ the Cherenkov light density L_{90} at $r = 90$ m and the light radius $R_L = -d \ln \rho(r)/dr$ in the region 50 m$< r <$120 m were derived.

For the analysis only well reconstructed showers with estimated energies E <320 TeV for photon-induced (<640 TeV for proton- and <1000 TeV for Fe-induced) showers were retained. The final data sample, which consists of 19.3 million showers, has the following characteristics : average zenith angle = 20°, average $\ln L_{90}$ = 9.16 (L_{90} in units of no. of photons / m^2), average $\log_{10}(N_s)$ = 4.12 and angular resolution = 0.12°.

The Monte Carlo (MC) simulation comprises the shower development in the atmosphere and the response of the detectors. A total of 2 660 000 showers was generated, with about equal numbers of showers for primary γ, p, He, O and Fe, at the zenith angles $\Theta = 10^\circ$, 20° and 30°.

The generated showers were given appropriate weights to simulate the chemical composition and the expected distributions in E and Θ. The differential fluxes and the spectral indices for the various components of the cosmic rays were taken from Wiebel-Sooth et al. (1998). For the comparisons with the experimental data an admixture of photons with a spectral index of 2.75 and a differential flux at 1 TeV of $\phi_0 = 0.0002582\ (\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{TeV})^{-1}$ has been assumed in the MC sample, corresponding to 1/1000 of the hadronic cosmic ray flux at 1 TeV.

In general the agreement between the MC data and the experimental data is quite good (Denninghoff (2001)). An exception is the distribution of $\log_{10}(L_{90})$ at $L_{90} < 10^4$. The discrepancy is partly attributed to the time dependence of the light of the night sky in the experimental data, which was not taken into account in the MC simulation.

From the MC data, which were subjected to the same selections as the experimental data, one finds :

– The energy region for reconstructed photon showers (10% and 90% quantiles) is $20\ \mathrm{TeV} < \mathrm{E}_\gamma < 100\ \mathrm{TeV}$, with an average energy of 53 TeV. The corresponding energies for reconstructed hadron showers are about a factor of 2 higher.

– Because photon showers of a given energy resemble hadron showers of about twice the energy, there is a natural suppression of hadron showers by a factor of ~ 3 due to the decreasing hadronic cosmic ray flux with increasing energy.

3 Results

The further analysis is based on photon/hadron differences in the shower development after the shower maximum. Because in a hadron shower the electromagnetic shower component is regenerated throughout the shower development by π^0 production and subsequent $\pi^0 \rightarrow \gamma\gamma$ decay, a hadron shower develops more slowly after the shower maximum than a photon shower. As a consequence, the average value of $\log_{10}(N_s/L_{90})$ at fixed position of the shower maximum (estimated by $1/R_L$) is smaller for photon than for hadron showers (Arqueros et al., 1996) (see Fig. 1). A suitable variable for the photon/hadron discrimination is therefore the variable v defined as (see Fig. 1)

$$v = \log_{10}(N_s/L_{90}[m^{-2}]) + 23.43 \cdot (0.005 - 1/R_L[m])$$

The MC expectations for the v distribution of photons and hadrons are displayed in Fig. 2. The differences in shape and position seen between these two distributions are exploited to determine the maximum contribution from photons which is still compatible with the experimental data. Two approaches will be followed

- Determination of a global upper limit by comparing the experimental distribution of v with the MC expectations for primary photons and hadrons (Sect. 3.1).

- Determination of an upper limit for a specific region in the galaxy by comparing the experimental distributions of v in this region with that of another region in the galaxy (Sect. 3.2).

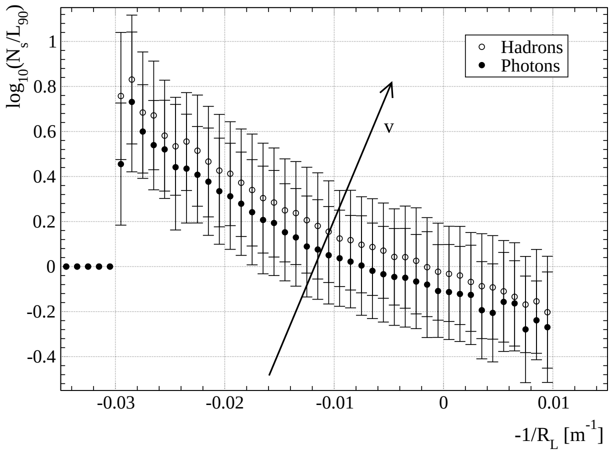

Fig. 1. Average value of $\log_{10}(N_s/L_{90})$ as a function of $(-1/R_L)$ for photon-induced (full circles) and hadron-induced (open circles) showers. The error bars represent the RMS of the $\log_{10}(N_s/L_{90})$ values in each bin of $(-1/R_L)$. The arrow indicates the axis of the variable v defined in the text.

3.1 Global upper limits of I_γ/I_{CR}

The distributions in v are denoted as

q_{data}	=	dN_{data}/dv	for the experimental data
q_γ	=	dN^γ_{MC}/dv	for MC-photon showers
q_h	=	dN^h_{MC}/dv	for MC-hadron showers

q_h and q_γ are normalized such that they correspond to the absolute distributions of reconstructed MC showers, assuming the same differential flux at 1 TeV of 0.2582 particles / $(\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{TeV})$ for photons and hadrons, the spectral indices mentioned above and an effective on-time of 1 s.

The ratio $r_0 = I^0_\gamma / I^0_{CR}$ of the differential photon flux I^0_γ and the differential hadron flux I^0_{CR} at 1 TeV is determined by fitting q_{data} by a superposition of q_h and q_γ :

$$q_{data} = c \cdot (q_h + r_0 \cdot q_\gamma)$$

c and r_0 are free parameters to be determined in the fit.

It is found that the width of the distribution q_{data} (RMS = 0.206) is slightly lower than that of q_h (0.224). These larger fluctuations of the MC data could have their origin in the shower simulation or may be due to a slight overestimation of the measurement errors in the MC data. To correct for this discrepancy the experimental distribution is smeared by distributing the content of one bin over the same bin and neighbouring bins according to a Gaussian. The sigma s of the Gaussian is determined as third parameter in the fit.

The experimental distribution q_{data} can be well fitted by a superposition of q_h and q_γ: the χ^2 is 88 for 85 degrees of freedom (see Fig. /reffig14). The pull values for the different bins in v are plotted in Fig. 4. The distribution of the pulls has an average of 0.21 and an RMS of 0.99. The results for the parameters r_0 and s are : $r_0 = 0.014 \pm 0.005$, $s = 0.080 \pm 0.003$. The quoted errors correspond to 1.282 sigma, so that $r_{0,upl} = r_0 + \Delta r_0 = 0.019$ is the upper limit of r_0 at the 90% confidence level, taking into account

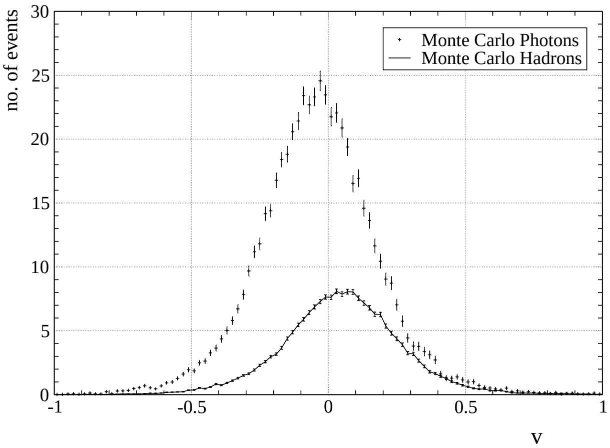

Fig. 2. Distribution of the variable v for MC-photon (upper distribution) and MC-hadron showers (lower distribution). The number on the y-axis is the number of reconstructed showers, assuming the same differential flux at 1 TeV of 0.2582 particles / $(\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{TeV})$ for photons and hadrons, the spectral indices mentioned in the text and an effective on-time of 1 s.

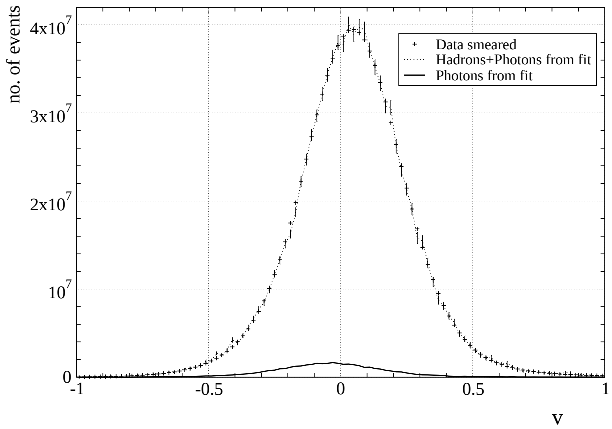

Fig. 3. Distribution of the variable v for the smeared experimental data (points with error bars). The dotted curve represents the fitted sum of the contributions from photons and hadrons, the solid curve the fitted contribution from photons only.

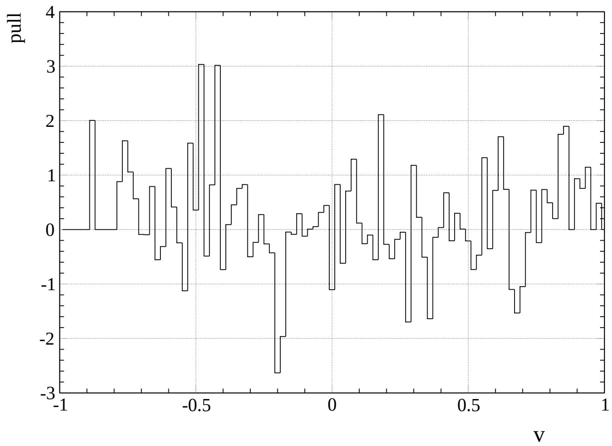

Fig. 4. The pull value as a function of the variable v. The pull value is defined as $(q_{fitted} - q_{data}) \;/\; \sqrt{(\Delta q_{fitted})^2 + (\Delta q_{data})^2}$.

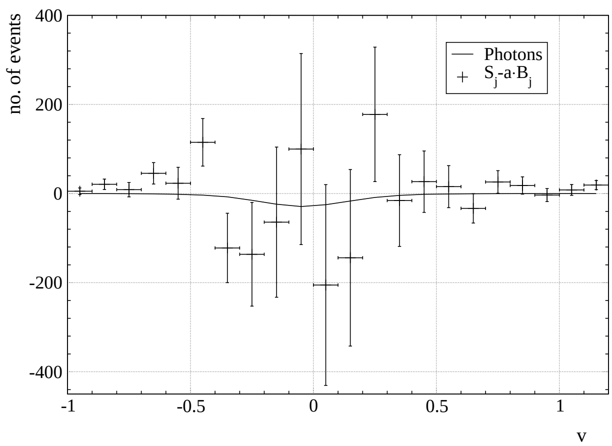

Fig. 5. Difference $(S_j - a \cdot B_j)$ between the v distributions of the signal and the background region (points with error bars). The solid curve represents the fitted contribution from photons $(a \cdot r_0 \cdot \epsilon \cdot G_j)$.

only the statistical errors. A careful analysis of the systematic errors shows that all systematic effects considered tend to lower the upper limit. Therefore $r_{0.upl}$ is the upper limit also if systematic errors are included.

The ratio $r_{0,upl}$ at 1 TeV is transformed to the average photon energy of the selected data sample of $\langle E_\gamma \rangle$ = 53 TeV, using the spectral indices of the photon and hadron fluxes adopted in the MC simulation. One obtains

$$I_\gamma/I_{CR}\ (\langle E\rangle = 53\ \mathrm{TeV})\ <\ 1.4 \times 10^{-2} \qquad \text{at 90\% c.l.}$$

The results presented sofar were obtained with event samples defined by the standard selections. Another fit was performed using tighter cuts in Θ and $(-1/R_L)$: $\Theta < 15°$ and $-0.01\ \mathrm{m}^{-1} < (-1/\mathrm{R_L}) < 0.01\ \mathrm{m}^{-1}$. The motivation for these selections is a stronger suppression of very-high-energy showers (Θ cut) and a rejection of showers with large penetration depths ($(-1/R_L)$ cut). The latter cut preferentially rejects hadron showers because they exhibit larger fluctuations in the shower development. An excellent fit is obtained with a χ^2 of 46.8 for 56 degrees of freedom. r_0 and $r_{0,upl}$ are determined as 0.012 and 0.016 respectively, yielding

$$I_\gamma/I_{CR}\ (\langle E\rangle = 31\ \mathrm{TeV})\ <\ 1.2 \times 10^{-2} \qquad \text{at 90\% c.l.}$$

3.2 Upper limit of I_γ/I_{CR} for the inner galaxy

The approach described in the previous section is subject to non-negligible systematic effects due to inconsistencies between the MC simulations and the experimental data. One may bypass these problems by looking for a photon signal using experimental data only, for example by comparing the experimental v distribution S of a sky region in which a photon contribution is expected (signal region) with the experimental v distribution B of a control region in which the photon contribution is negligible (background region). The MC simulation is then only needed to parametrize position and shape of the expected photon contribution G in the signal region and to convert the photon signal (given in terms of numbers of events) into a photon flux.

The signal and background regions are defined as :

signal region : $20^\circ < l < 60^\circ$, $|b| < 5^\circ$
background region : $20^\circ < l < 60^\circ$, $10^\circ < |b| < 30^\circ$,

where l and b are the Galactic longitude and latitude respectively. With this definition the average l of the events in the signal region is 48.6°. The average l and $|b|$ of the events in the background region are 45.7° and 20° respectively.

The acceptance of the detector depends strongly on the zenith angle Θ, due to the varying overburden in the atmosphere. It also depends on Θ and the local azimuthal angle ϕ, due to the construction of the detector. Finally, because of varying atmospheric conditions and because of possible changes in the hardware, the acceptance is also a function of the time t. Therefore the v distribution will in general depend on (Θ, ϕ, t). Since the data for the signal and the background regions are taken in different regions of the (Θ, ϕ, t) space, special care has to be taken to avoid any bias when comparing the v distributions S and B.

This is achieved by the following procedure. The experimental data are divided into 12 bins in $\cos\Theta$, 18 bins in ϕ and 352 bins in t. One time bin was defined as the minimum number of full nights, with a total observation time of at least 5 hours, corresponding to a right ascension scan of $\geq 75^\circ$. Within each bin of the $(\cos\Theta, \phi, t)$ space the v distributions of photons and hadrons are assumed to be independent of $(\cos\Theta, \phi, t)$.

If i denotes the i-th bin in the $(\cos\Theta, \phi, t)$ space, N_i (M_i) the number of events in bin i from the signal (background) region, and v_i (w_i) the normalized v distribution in bin i for the signal (background) region, S and B are defined as

$$S = \sum_i N_i v_i, \qquad B = \sum_i N_i w_i$$

In order to ensure that the background distribution w_i is at least as well determined as the signal distribution v_i only those i are included in the sums for which $M_i > N_i$. By weighting the v distribution w_i with N_i the systematic effects which are present in S are simulated in B. Differences between the shapes of S and B are now interpreted as being due to different contributions of photons.

The ratio $r_0 = I^0_\gamma / I^0_{CR}$ at 1 TeV is determined by fitting the signal distribution S by a superposition of the background distribution B and a term G, representing a possible contribution from photons :

$$S = a \cdot (B + r_0 \cdot \epsilon \cdot G)$$

For G the MC expectation q_γ (see above) for reconstructed photon showers is taken, rebinned and normalized to $\sum_i N_i$ reconstructed events. ϵ (= 1/0.348) is an average ratio of the number of reconstructed photon to the number of reconstructed hadron showers, assuming the same differential flux of photons and hadrons at 1 TeV. The parameters a and r_0 are adjusted in the fit. The result of the fit is $r_0 = -(0.0003 \pm 0.0030)$, with a χ^2 of 26.6 for 20 degrees of freedom. Transforming $r_{0,up} = r_0 + \Delta r_0 = 0.0027$ to the average photon energy of 54 TeV yields the upper limit

$$I_\gamma / I_{CR} \ (\langle E \rangle = 54 \text{ TeV}) \ < \ 2.0 \times 10^{-3} \qquad \text{at 90\% c.l.}$$

The difference $(S - a \cdot B)$ is shown in Fig. 5, together with the fitted contribution from photons $(a \cdot r_0 \cdot \epsilon \cdot G)$.

4 Discussion

The global upper limits $I_\gamma/I_{CR}(\langle E \rangle = 53 \text{ TeV}) < 1.4 \times 10^{-2}$ and $I_\gamma/I_{CR}(\langle E \rangle = 31 \text{ TeV}) < 1.2 \times 10^{-2}$ are measurements which are sensitive to both the isotropic and the non-isotropic component of the diffuse photon radiation. Measurements of this kind in the 20 TeV to 100 TeV energy range were also reported by Karle et al. (1995) and Sasano et al. (1999). All upper limits are in the range 1.0 % to 6.7 %, about 1 to 2 orders of magnitude above the prediction by Porter and Protheroe (1999) for the Galactic component near the Galactic disk.

Porter and Protheroe (1999) give predictions for cutoff energies in the electron injection spectrum of 100 TeV and 1000 TeV respectively. The upper limit $I_\gamma/I_{CR}(\langle E \rangle = 54 \text{ TeV}) < 2.0 \times 10^{-3}$ is a factor of $\sim$10 above the former and a factor of $\sim$3 above the latter prediction. This measurement is sensitive to the non-isotropic component of the diffuse photon radiation only.

An earlier measurement by the HEGRA collaboration (Schmele (1998)), $I_\gamma/I_{CR}(E > 42 \text{ TeV}) < 1.6 \times 10^{-4}$ for $0^\circ < l < 255^\circ$, $|b| < 5^\circ$, which is based on data taken with the array of scintillators, excludes the cutoff energy of 1000 TeV and is compatible with a cutoff energy of 100 TeV. The same holds for the measurement by Borione et al. (1998) : $I_\gamma/I_{CR}(E = 140 \text{ TeV}) < 3.4 \times 10^{-5}$ for $50^\circ < l < 200^\circ$, $|b| < 5^\circ$.

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