Indications for a suppression of pair production at very high energies

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The transparency of the universe for very high energy (VHE) photons is limited due to pair-production with low energy photons of the extra galactic background light (EBL) in the ultra-violet to infrared wavelength band. Here, we use 58 energy spectra from VHE emitting active galactic nuclei (AGN) from redshift 0.004 to 0.536 to search for signatures of deviations from the minimum expected opacity. A statistical study of the individual measurements reveals indications for an overcorrection of AGN spectra with current EBL models. Axion like particles are discussed as a possible explanation of the result.

1 Introduction

The opacity of the universe for very high energy (VHE, energy $E \gtrsim 100\,\mathrm{GeV}$) photons arises through the interaction with background radiation fields, $\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{bkg}} \rightarrow e^{+} + e^{-}$. The photon flux $\mathrm{d}N_{\mathrm{int}}/\mathrm{d}E$ of a cosmological source with redshift z corrected for absorption is commonly expressed as

$$\frac{\mathrm{d}N_{\mathrm{int}}}{\mathrm{d}E} = \frac{\mathrm{d}N_{\mathrm{obs}}}{\mathrm{d}E} \times \exp\left[\tau_{\gamma\gamma}(E, z)\right], \tag{1}$$

where the observed spectrum is denoted as $\mathrm{d}N_{\mathrm{obs}}/\mathrm{d}E$. The optical depth $\tau_{\gamma\gamma}$ is a threefold integral over the cross section for pair production multiplied with the number density of background photons over the cosmological distance, the cosine of the angle between the photon momenta, and the energy of the background photons. The cross section for pair production strongly peaks at a wavelength $\lambda = 1.24(E/\mathrm{TeV})$ m which makes the extragalactic background light (EBL) the dominant radiation field responsible for the attenuation of VHE photon fluxes. The EBL ranges from the ultra-violet / optical to the far infrared wavelength band and originates mainly from starlight integrated over all epochs and starlight that has been reprocessed by dust in galaxies [1]. These two contributions lead to two peaks in the spectral energy distribution (SED) of the EBL: the first at around 1 m for the emitted starlight and at around 100 m for the re-emitted dust component. Direct measurements of the EBL are challenging due to the contamination with foreground emission such as the zodiacal light [2] and, therefore, a number of models have been published in the past that forecast the EBL density [3, 4, 5, for some recent examples].

In grand unified theories that aim to combine the standard model of particle physics with gravity, effects can occur that alter the opacity of the universe. This is for example the case in certain quantum gravity theories that predict the breakdown of Lorentz invariance [6, 7] or in the presence of particles like axions or axion like particles (ALPs) [8, 9, 10, 11, 12]. In the case of Lorentz invariance violation (LIV), an energy dependent time delay of photons is predicted as well as a shift of the threshold energy for pair production. The latter effect alters $\tau_{\gamma\gamma}$ at a fixed energy. On the other hand, in ALP scenarios, photons can convert into ALPs in magnetic fields that pervade the source, the Milky Way and presumably in the intergalactic medium. The effect of photon-ALPs oscillation is twofold. Fluxes of photons for which the universe appears optically thin, i.e. whose energies and source distances translate into small values of $\tau_{\gamma\gamma}$, are additionally dimmed as the photons convert to ALPs which are not detected on earth. With increasing $\tau_{\gamma\gamma}$, the photon-ALP conversion probability increases so the probability is higher that ALPs convert back into photons. Consequently, the attenuation is decreased as ALPs are not subject to pair production. As a result, the applied correction for fluxes of photons for which the universe is optically thick will be too large and a hardening of the intrinsic spectra is expected.

In this article we statistically investigate 58 VHE spectra from 25 sources obtained with the imaging air Cherenkov telescopes CAT, HEGRA, H.E.S.S., MAGIC, VERITAS and WHIPPLE for a systematic effect in the transition from the optical thin to optical thick regime. This guarantees that the results derived here are independent from source physics as $\tau_{\gamma\gamma}$ is a nontrivial combination of the energy of the γ-ray photon and the distance of the source. The observed spectra are corrected for the EBL absorption with Eq. 1 and using the lower limit EBL model by [4]. This lower limit model predicts the guaranteed level of EBL density which is just in agreement with the $1\,\sigma$ downward fluctuation of the galaxy number counts obtained with *Spitzer* [13] and gives the lowest possible absorption.

The considered sources are all active galactic nuclei (AGN) with known redshift[1]. It follows from Eq. 1 and from the ignorance of the exact shape of the SED of the EBL that it is impossible to measure the intrinsic source spectrum directly. The measured photon indices[2] vary between ~ 1.4 and ~ 4 which makes it difficult to infer some generic intrinsic spectrum valid for all blazars. Furthermore, the source sample might suffer from observational bias, i.e. only certain sources are detected at large redshifts.

These difficulties stress the necessity that the statistical test introduced here is independent of any assumptions of the intrinsic VHE spectra and / or their distance alone.

2 A statistical test to search for an overcorrection of VHE spectra

As a compromise between number of spectra and the strength of the expected effect, we define optical thick as $\tau_{\gamma\gamma} \geq 2$ and optical thin as $\tau_{\gamma\gamma} < 2$. This value of the optical depth also ensures that the dimming due to pair production is not confused with the dimming of the initial flux because of photon-ALPs conversion. The latter can reduce the initial photon flux by maximally 1/3 [8] which already occurs for $\tau_{\gamma\gamma} \approx 0.4$.

The statistical test is devised as follows. For a given VHE spectrum the data points are determined that correspond to an optical depth $\tau_{\gamma\gamma} < 1$. These points are then fitted with a power law using a χ^2-minimization algorithm. If the resulting p-value of the fit is less than

[1] Sources for which the redshift is under discussion (e.g. 3C 66A, PG 1553+113 and S 50716+714) are not included in the analysis.

[2] Most observed VHE spectra are adequately described by power laws of the form $\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma}$, where Γ is called the photon index, see also Table 1.

Table 1: Analytical functions used to fit the data points of the spectra. The smoothing parameter f of the broken power law is fixed to 4 and the energy normalization E_0 is set to 1 TeV.

Function Name	$\mathrm{d}N/\mathrm{d}E(E)$	Fit parameters
Power law	$N_0(E/E_0)^{-\Gamma}$	N_0, Γ
Logarithmic parabola	$N_0(E/E_0)^{-(\Gamma+\beta\ln(E/E_0))}$	N_0, Γ, β
Broken power law	$N_0(E/E_0)^{-\Gamma_1}[1+(E/E_{\mathrm{break}})^f]^{(\Gamma_1-\Gamma_2)/f}$	N_0, Γ_1, Γ_2, E_{break}

5 % a logarithmic parabola is fitted instead and if the p-value still remains below 5 % a broken power law is used. The analytic functions are summarized in Table 1.

The functions determined this way are extrapolated to all remaining data points. As an example, the procedure is shown in Fig. 1 for the spectrum of 1ES 1101-232 measured with H.E.S.S. [14]. The deviation of the i-th data point from the extrapolation is quantified by the ratio R_i,

$$R_i = \frac{\varphi_i - f^{\mathrm{ext}}(E_i)}{\varphi_i + f^{\mathrm{ext}}(E_i)}. \tag{2}$$

Here, f^{ext} denotes the extrapolation of the analytic description of the data points with $\tau_{\gamma\gamma} < 1$ and φ_i is the shorthand notation for $\mathrm{d}N_i^{\mathrm{int}}/\mathrm{d}E_i$. For our purposes to find an overcorrection of the observed spectra, the choice of analytical functions can be considered conservative as they show less curvature than e.g. a power law modified with an exponential cut-off. The extrapolation of such a function could lead to an overestimation of R for the highest energy bins. The ratios are calculated for all considered VHE spectra[3] and two distributions of ratios are defined that correspond to optical thin and thick measurements, respectively,

$$\mathcal{S}_{\mathrm{thin}} = \{R_i \mid 1 \leq \tau_{\gamma\gamma}(E_i, z) < 2\}, \tag{3}$$

$$\mathcal{S}_{\mathrm{thick}} = \{R_i \mid \tau_{\gamma\gamma}(E_i, z) \geq 2\}. \tag{4}$$

These two distributions are compared with the Kolmogorov-Smirnov (KS) test [16, 17] under the null-hypothesis that the underlying probability distributions are equal.

3 Results

From the 58 spectra, only 28 (8) spectra have data points that correspond to an optical depth ≥ 1 (≥ 2). Figure 2 shows the result of the KS-test. The left panel displays the ratios R for each data point of every spectrum plotted against the optical depth. It can be seen that spectra of distant sources measured up to several hundreds of GeV along with spectra of sources close by and detected beyond tens of TeV contribute to the $\mathcal{S}_{\mathrm{thick}}$ sample. A trend is visible that observations at large $\tau_{\gamma\gamma}$ tend to show higher values of R as well. This is confirmed in the right panel which depicts the corresponding cumulative distribution functions (CDFs). About 60% of the ratios in $\mathcal{S}_{\mathrm{thin}}$ are below zero and not 50% as one would naively expect. The reason for this might be an intrinsic curvature of the spectra or an underestimation of the EBL density for $1 \leq \tau_{\gamma\gamma} < 2$ by the lower limit model. In the case of the extrapolation to values that correspond $\tau_{\gamma\gamma} \geq 2$, the CDF of $\mathcal{S}_{\mathrm{thick}}$ shows a systematic increase towards higher values of

[3] For the entire VHE sample considered here, see [15] and references therein.

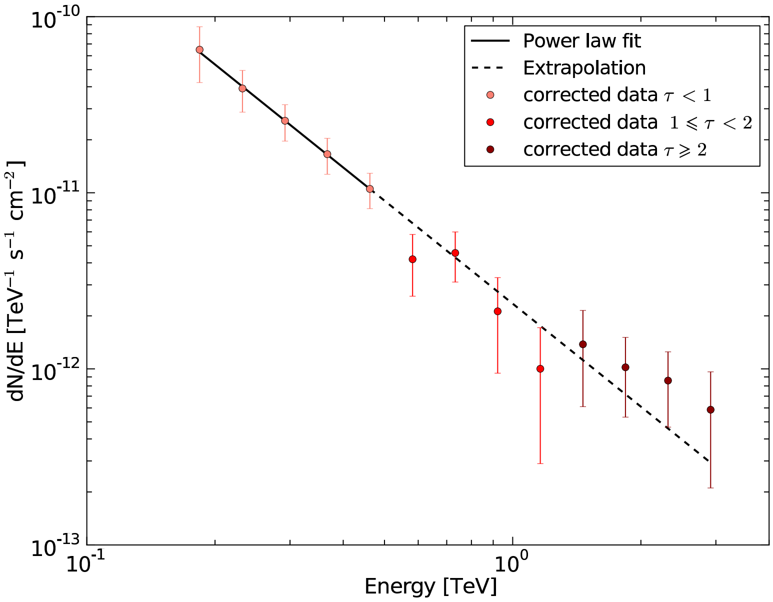

Figure 1: The spectrum of 1ES 1101-232 measured with H.E.S.S. [14] with $1\,\sigma$ statistical errors on the flux. The first five points correspond to a $\tau_{\gamma\gamma}$ value smaller than one and thus enter into the power-law fit. The fit itself is shown as a black solid line. The fit is extrapolated to all other points (dashed line) and the ratios R_i are calculated according to Eq. 2. The ratios of the red points enter $\mathcal{S}_{\mathrm{thin}}$ while the ratios of the dark red points contribute to $\mathcal{S}_{\mathrm{thick}}$, see Eq. 3 and 4.

R, indicating a hardening of the intrinsic spectra which can be taken as evidence that the correction is indeed too strong. The maximum distance D between the CDFs of $\mathcal{S}_{\mathrm{thin}}$ and $\mathcal{S}_{\mathrm{thick}}$ is found to be $D \approx 0.68$ for which the KS-test gives a probability of $Q_{KS} \approx 3.78 \times 10^{-5}$ that the underlying probability distributions are equal. This corresponds to a significance of $3.96\,\sigma$ (one-sided confidence interval) that they are different from each other. A cross check with galactic sources shows that this result cannot be explained by instrumental effects such as an overestimation of the flux in the highest energy bins [15].

4 Conclusion

In this article a new approach based on the Kolmogorov-Smirnov test is presented that searches for systematic changes in VHE spectra corrected for the EBL absorption in the transition from $\tau_{\gamma\gamma}(E,z) < 2$ (optically thin) to $\tau_{\gamma\gamma}(E,z) \geq 2$ (optically thick). The approach is independent of the exact shape of the intrinsic VHE spectra and, thus, the obtained results do not suffer from possible observational bias, e.g. only certain types of sources are detected at high redshifts. Furthermore, the test is designed to be independent of the statistical uncertainties of the individual flux measurements as they seem to be overestimated independent of the telescope that observed the source [15].

An indication with a significance of $3.96\,\sigma$ is found that optically thick measurements are over

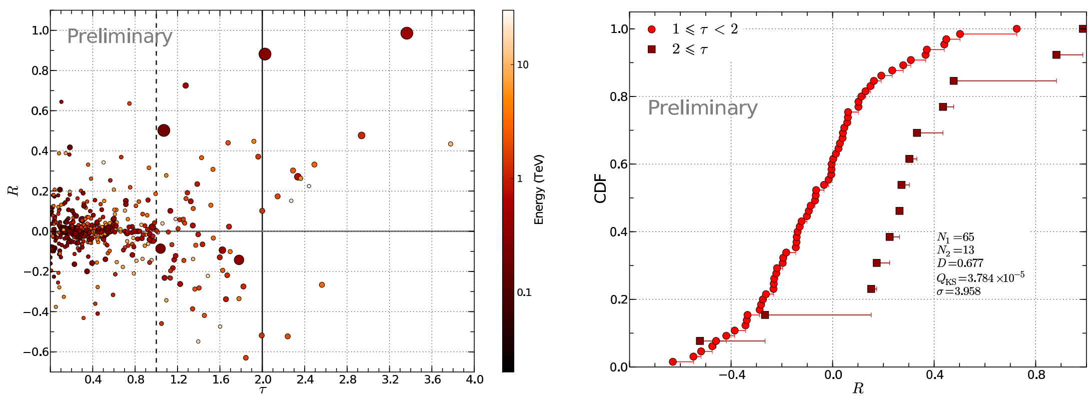

Figure 2: Result of the KS-test. Left Panel: The Ratios R plotted against the Optical depth $\tau_{\gamma\gamma}$. The size of the markers is proportional to the redshift while the color encodes the corresponding energy of each data point. Right panel: CDFs of $\mathcal{S}_{\text{thin}}$ and $\mathcal{S}_{\text{thick}}$.

corrected by a lower limit EBL model. If the significance of this result is confirmed and improved with future observations[4] it demands for an explanation other than tuning the EBL density as the lower limit model already predicts a minimum attenuation that is in accordance with lower limit measurements of the EBL. The result is difficult to explain with source physics since many objects measured at different redshifts and energies enter the test. For instance, an upturn of the intrinsic spectra at multiple TeV energies caused by effects like second order inverse Compton scattering [18], comptonization of cosmic microwave background (CMB) photons [19], or interactions of ultra-high energy cosmic rays with the CMB [20, 21, 22] are not able to explain our findings. One the one hand, such features could possibly enter the ratios of $\mathcal{S}_{\text{thin}}$ and $\mathcal{S}_{\text{thick}}$ since they are distinguished by $\tau_{\gamma\gamma}$ and not by the energy E. On the other hand, distant sources like 3C 279 measured below 1 TeV also contribute to the result. One candidate for a way out might be given by photon-ALPs conversion as theory predicts a decrease of the attenuation for large values of the optical depth.

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