Indications for a transparent universe at very high energies

Manuel Meyer¹ and Dieter Horns¹

¹Institut für Experimentalphysik, University of Hamburg, Luruper Chaussee 149, 22767 Hamburg, Germany
E-mail: manuel.meyer@physik.uni-hamburg.de

Abstract. The transparency of the universe for very high energy (VHE) photons is limited due to pair-production with low energy photons of the extragalactic background light (EBL) in the optical to infrared band. Here, we use 56 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) photons (with an energy $E \gtrsim 100$ GeV) arises through the pair production process in the interaction with background radiation fields, $\gamma_{\text{VHE}} + \gamma_{\text{bkg}} \rightarrow e^+ + e^-$. As a consequence, the intrinsic photon flux $dN_{\text{int}}/dE$ of a cosmological source with redshift $z$ is dimmed which is commonly expressed as

$$\frac{dN_{\text{obs}}}{dE} = \frac{dN_{\text{int}}}{dE} \times \exp\left[ -\tau_{\gamma\gamma}(E,z) \right],$$

where the observed spectrum is denoted as $dN_{\text{obs}}/dE$. The optical depth $\tau_{\gamma\gamma}$ is a threefold integral over the cross section for pair production and 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 the pair production strongly peaks at a wavelength $\lambda = 1.24 (E/\text{TeV}) \mu\text{m}$ which makes the extragalactic background light (EBL) the radiation field responsible for the attenuation of VHE photon fluxes. The EBL ranges from the UV/optical to the far infra-red wavelength band and originates mainly from starlight integrated over all epochs and starlight that has been absorbed and re-emitted 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 $\mu$m for the emitted starlight and at around 100 $\mu$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. Therefore, in the past years many models have emerged that try to describe the EBL [2][3][4], for some recent examples.

In grand unified theories that aim to combine the standard model (SM) 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 [5][6] or in the presence of exotic particles like axions or axion like particles (ALPs) [7][8][9][10][11]. Here, the attention is focused on ALPs. 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
photon index, see also Table 1. Most observed VHE spectra are adequately described by power laws of the form $dN/dE \propto E^{-\Gamma}$, where $\Gamma$ is called the photon index, see also Table 1.

As discussed in the introduction, an overcorrection of the observed spectra in the presence of ALPs is expected for high values of $\tau_{\gamma\gamma}$. This guarantees that our results are as independent from source physics as possible as $\tau_{\gamma\gamma}$ is a nontrivial combination of the energy of the $\gamma$-ray photon and the distance of the source. For example, high values of the optical depth may be the result of a distant source (like 3C 279) at several hundreds of GeV or for a relatively close source (like Markarian 501) measured at tens of TeV. The observed spectra are corrected for the EBL absorption by inverting Eq. 1 and using the lower limit EBL model by [3]. This lower limit model predicts an EBL which is just in agreement with the $1\sigma$ downward fluctuation of the galaxy number counts by Spitzer [12] and gives the lowest possible absorption. This ensures that our results indeed indicate a new phenomenon rather than reflecting the uncertainties of the EBL modeling.

The considered sources are all active galactic nuclei (AGN) with known redshift. 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 vary between $\sim 1.4$ and $\sim 4$ 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 $\gamma$ or their distance alone. An additional advantage of the test presented in the next section is its independence of the statistical uncertainties of the single measurements.

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

In this article we statistically investigate 55 VHE spectra from 25 sources obtained with the imaging air Cherenkov telescopes CAT, HEGRA, H.E.S.S., MAGIC, VERITAS and WHIPPLE for an overcorrection of the observed spectrum for high values of $\tau_{\gamma\gamma}$. This corresponds to a combination of a high redshift of 3C 279 at several hundreds of GeV or a relatively close source (like Markarian 501) measured at tens of TeV. The observed spectra are corrected for the EBL absorption by inverting Eq. 1 and using the lower limit EBL model by [3]. This lower limit model predicts an EBL which is just in agreement with the $1\sigma$ downward fluctuation of the galaxy number counts by Spitzer [12] and gives the lowest possible absorption. This ensures that our results indeed indicate a new phenomenon rather than reflecting the uncertainties of the EBL modeling.

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| Function Name       | $dN/dE(E)$                     | Fit parameters |
|---------------------|--------------------------------|----------------|
| Power law           | $N_0(E/E_0)^{-\Gamma}$        | $N_0, \Gamma$  |
| Logarithmic parabola| $N_0(E/E_0)^{-\Gamma+\beta \ln(E/E_0)}$ | $N_0, \Gamma, \beta$ |
| Broken power law    | $N_0(E/E_0)^{-\Gamma_1}[1 + (E/E_{\text{break}})^\beta]^f(\Gamma_1-\Gamma_2)/f$ | $N_0, \Gamma_1, \Gamma_2, E_{\text{break}}$ |

The statistical test is devised as follows. For a given VHE spectrum the data points are determined

1. Sources for which the redshift is under ongoing discussion such as 3C 66A, PG 1553+113 and S 50716+714 are not considered either.
2. Most observed VHE spectra are adequately described by power laws of the form $dN/dE \propto E^{-\Gamma}$, where $\Gamma$ is called the photon index, see also Table 1.
that correspond to an optical depth $\tau_{\gamma\gamma} < 1$. To these points a simple power law is fitted using a $\chi^2$-minimization algorithm. If the resulting $p$-value of the fit is less than 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.

However, only for 5 spectra other functions than a power law are necessary to describe the data. These are spectra from Markarian 421 and Markarian 501 which are close sources with redshifts of 0.031 and 0.034, respectively, and one spectrum of PKS 2155-304. Already the observed Markarian spectra show curvature and since they are relatively close by many data points enter the fit. In the case that the spectrum only contains one data point with $\tau_{\gamma\gamma} < 1$ it is not considered, if it contains two data points the fit parameters of the power law are derived analytically.

![Figure 1](image-url)

**Figure 1.** The spectrum of 1ES1101-232 measured by H.E.S.S. [13] 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 the 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 $S_{\text{thin}}$, while the ratios of the dark red points contribute to $S_{\text{thick}}$, see Eq. 3 and 4.

The functions determined this way are extrapolated to all remaining data points. The procedure is shown in Fig. 1 for the spectrum of 1ES1101-232 measured by H.E.S.S. [13]. The deviation of the $i$-th data point from the extrapolation is quantified by the ratio $R_i$.

$$R_i = \frac{\ln f^{\text{ext}}(E_i) - \ln f^{\text{int}}_i}{\ln f^{\text{ext}}(E_i) + \ln f^{\text{int}}_i}. \quad (2)$$

Here, $f^{\text{ext}}$ denotes the extrapolation of the analytic description of the data points with $\tau_{\gamma\gamma} < 1$ and $f^{\text{int}}_i$ is the shorthand notation for $dN^{\text{int}}_i/dE$. If the corrected data point lies above the extrapolation, $R$ will be positive since $f^{\text{ext}}$ and $f^{\text{int}}$ are always smaller than one. Simulations show that this definition of $R$ gives the most sensitive result for the statistical test [14], opposed to e.g. a definition without the logarithm.
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 because 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,

$$S_{\text{thin}} = \{ R_i \mid \tau_{\gamma\gamma}(E_i, z) < 2 \}, \quad (3)$$

$$S_{\text{thick}} = \{ R_i \mid \tau_{\gamma\gamma}(E_i, z) \geq 2 \}. \quad (4)$$

These two distributions are compared with the Kolmogorov-Smirnov (KS) test\(^15\) under the null-hypothesis that the underlying probability distributions are equal.

### 3. Results

From the 56 spectra, only 26 (7) spectra have data points that correspond to an optical depth $\geq 1$ ($\geq 2$). Figure 2 shows the result of the KS-test. The upper panel displays the optical depth for each data point of every spectrum plotted against the ratios $R$ with their corresponding errors (only the errors of the individual flux measurements are considered). The red points contribute to the $S_{\text{thick}}$ distribution whereas the blue points all correspond to an optical depth of $1 \leq \tau_{\gamma\gamma} < 2$ and are thus part of $S_{\text{thin}}$. From the discussion in Section 2 it is clear that the number of points in $S_{\text{thick}}$ (labeled $N_1$ in the figure) is smaller than in $S_{\text{thin}}$ (labeled $N_2$) since less observations are available for such large attenuations. 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 lower panel which depicts the corresponding cumulative distribution functions (CDFs). The green line simply visualizes that the analytical functions are a good description of the observations as the data points that enter the fit itself also enter into this CDF. The situation is different for the extrapolated data points. The blue line represents the CDF of $S_{\text{thin}}$. About 60% of the ratios are below zero and not 50% as one would naively expect. The reason for this might be an intrinsic curvature of the spectrum 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 (red line) show a systematic increase towards higher values of $R$, 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 $S_{\text{thin}}$ and $S_{\text{thick}}$ is found to be $D \approx 0.62$ for which the KS-test gives a probability of $Q_{\text{KS}} \approx 2.81 \times 10^{-4}$ that the underlying probability distributions are equal. This corresponds to a significance of $3.45\sigma$ (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\(^1\)\(^4\).

### 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.

An indication with a significance of $3.45\sigma$ is found that optically thick measurements are overcorrected by a lower limit EBL model. If the significance of this result is confirmed and improved with future observations\(^5\), 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

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\(^3\) For the entire VHE sample considered here, see [14] and references therein.

\(^4\) There are $O(10)$ new detections of VHE emitting AGN announced, see e.g. \url{http://tevcat.uchicago.edu}
different redshift and energy enter the test. For instance, an upturn of the intrinsic spectra at multiple TeV energies due to e.g. second order inverse Compton scattering \cite{17}, comptonization of cosmic microwave background (CMB) photons \cite{18} or interactions of ultra-high energy cosmic rays with the CMB \cite{19, 20, 21} is not able to explain our findings. One the one hand, such features could possibly enter the ratios of $S_{\text{thin}}$ and $S_{\text{thick}}$ since they are disinguished 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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