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Probing Gamma-Ray Propagation at Very-High Energies with H.E.S.S. Observations of M87

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The radio galaxy Messier 87 has an active galactic nucleus, from which observations have been made of very high energy (E > 100 GeV) γ-rays up to a few 10s of TeV using the H.E.S.S. telescope array. During monitoring campaigns and target of opportunity observations, several high flux states could be identified. The high photon statistics obtained during these states allow us to probe phenomena affecting VHE γ-ray propagation across cosmic distances. Interaction of these photons with the Extragalactic Background Light (EBL) causes an attenuation, leading to an observed cut-off in the spectra of very high energy sources. Observations of M87 can be utilized to make measurements of the local EBL, specifically in the far infrared range. Furthermore, M87 is located at the heart of the nearby Virgo galaxy cluster located 18 Mpc away which is host to an intra-cluster magnetic field calculated at 34.2 μG. This allows us the opportunity to probe for effects of the mixing of light pseudo-scalar Axion Like Particles (ALPs) with photon states. These dark matter candidates are predicted to exhibit an oscillation effect in the presence of magnetic fields, oscillating between photon and ALP states. This energy-dependent effect would lead to the disappearance of photons, which would result in measurable "wiggles" in the source's spectra. We find that the collected photon statistics do not suffice to significantly detect or constrain the ALP-photon coupling.

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1. Introduction

Messier 87 is an active galactic nucleus (AGN) located centrally in the Virgo cluster. Very high energy (VHE; E > 100 GeV) γ-ray photon statistics obtained from the sources during high states offer us an opportunity to probe phenomena that affect photon propagation across cosmic distances. We probe two specific phenomena which might play a relevant role in this propagation [5]: Extra-galactic Background Light (EBL) attenuation and photon-ALP oscillations in the presence of astrophysical magnetic fields, where ALP stands for axion-like particle. M87 is located relatively close to us, at a redshift of around 0.0042 corresponding to a luminosity distance of 18.2 Mpc. In the scope of this study, we specifically analyse observations of M87 made during high/flaring states using the High Energy Stereoscopic System (H.E.S.S.) Cherenkov telescope array. We have observed statistics up to a few tens of TeV, which offers us the opportunity to probe the EBL at the far-infrared energies, which still is not very well constrained. Further, the Virgo cluster which hosts M87 near its center is also a host to a strong intra-cluster magnetic field. This allows us to probe the existence of photon-ALP oscillations during propagation through this magnetic field.

We begin by establishing the best parametrization for the intrinsic spectrum of the source, after which we attempt to probe and constrain the normalization of the EBL in the far-infrared photon energy range. Proceeding this, we fit our data against simulated models of photon-ALP oscillations occurring during the propagation of VHE γ-ray photons through the Virgo cluster's magnetic field, and toward our detectors. We use this method to search for photon-ALP oscillation signatures in the γ-ray spectrum. The methods and results concerning this study have been summarized in the the following sections. More detailed information about the photon-ALP oscillation models and the EBL constraints can be found in our other publications [6, 11].

2. H.E.S.S. Observations

For the purposes of this study our interest lies in the VHE γ-ray observations of M87 made during high/flaring states using the H.E.S.S. Cherenkov telescope array. The High Energy Stereoscopic System or H.E.S.S., is an array of five Imaging Air Cherenkov Telescopes located in the Khomas highlands in Namibia. The array consists of four smaller telescopes with an effective mirror diameter of 12 m named CT1-CT4, and a large telescope with an effective mirror diameter of 28 m named CT5. New cameras were installed on the smaller telescopes CT1-4 between 2015 and 2016, and a new camera was installed in 2019 for CT5. H.E.S.S. can detect very high energy γ-rays between $\sim$ 50 GeV and $\sim$ 100 TeV. M87 has been observed with H.E.S.S. in high states during 2005, 2010 and 2018. We focus on observations made during these high states to attempt to exploit the increased flux of very high energy photons emitted at this time. We extract and reduce data within an energy range of 300 GeV - 31.6 TeV. We avoid statistics below 300 GeV to avoid systematic uncertainties in the Instrument Response Function (IRF). We limit ourselves to observation runs with a minimum of 3 telescopes participating, with a mean zenith angle < 57.7°, and between the years 2004 and 2022. We further select runs with only high count rates, specifically those runs which have a rate exceeding 0.2 excess min^{-1} above 1 TeV. We perform the data reduction and analyses using the gammapy (v1.01) python package [8]. The data was reduced using the std zeta cut configuration [12]. The data is processed and spectra are extracted from each observation and stacked for further analyses. From the dataset we reduce, the source has been detected with an excess count of 342, a background of 283 and a total livetime of ∼17.1 hrs. Further information can be found in our associated publication [11]. A cross-check with an independent analysis chain [7] yields consistent results.

3. Extragalctic Background Light

The EBL is a diffuse photon background that is present across the Universe. It primarily consists of photons emitted from star formation, dust re-emission and AGNs [10]. This background spans a broad energy range, but here we focus on the far-infrared region of the spectrum. High energy photons interact with the EBL, leading to an attenuation of our VHE photon signal as it propagates toward our detectors. For our source, which is located at a redshift of $z = 0.0042$, this attenuation only begins to dominate above ∼10 TeV. We rely on the VHE events observed in the source during its high states to attempt to place constraints on the EBL normalization. When applying an EBL model, it generally follows the equation:

$$\exp\left(-\alpha \times \tau(E, z)\right) \tag{1}$$

Here, τ is the optical depth provided by the chosen EBL model, and α is the normalization of the model. For the purposes of our analysis, we use the optical depth values from the Dominguez et. al. model [9], provided in the ebltable software package.[1] By default the EBL models in gammapy assume the model with a set normalization of $\alpha = 1$. We free the normalization and attempt to constrain this against our statistics. More information on our results and how we perform this study can be found in our paper [11]. The result in simple terms is that we are able to place an upper limit on the normalization of the EBL at $\alpha \leq 2.82$ with 95% confidence.

4. Intrinsic Spectrum

The first step in our analysis is to determine the shape of the intrinsic spectrum of our source. In order to compare and select an optimal intrinsic spectral model, we sequentially fit with a power law and a Log Parabola. We then compare the likelihood of each fit using their C-statistic values. When performing fits, gammapy returns a value termed total stat which represents the C-statistic of the fit. This C- stat value is determined by the equation [18]:

$$C = -2\ln\mathcal{L}(\mu, b; \alpha_{exp}|n_{On}, n_{Off}) = n_{On}\ln(\mu + b) + n_{Off}\ln(b/\alpha_{exp}) - b/\alpha_{exp} \tag{2}$$

where $\mathcal{L}$ is the likelihood, μ is the expected number of counts, n_{On} is the number of counts in the signal region, n_{Off} is the number of counts in the background region and α_{exp} is the exposure ratio between these two regions. In simple terms, a lower C value represents a higher likelihood. This likelihood depends on the spectral parameters. Our fits conclude that a Log Parabola is the optimal model for the shape of the intrinsic spectrum with $\Delta C = C_{PL} - C_{LP} = 29.76$. This proves interesting as this curvature was not necessarily expected from the source in these energy ranges.

[1]https://github.com/me-manu/ebltable

Further follow-up on this might prove interesting in the scope of other studies. We further probe this in depth by performing the same fits in a more limited energy range between 300 GeV and 10 TeV. The Dominguez EBL model [9] gives us an optical depth $\tau = 0.13$ at 10 TeV. Thus by excluding energies above 10 TeV, we effectively exclude contributions from the EBL toward the spectral shape. We still see a preference of 5.4σ for the Log Parabola over the power law. This is discussed further in our forthcoming paper [11].

5. ALP Searches

Axions are theoretically motivated pseudo-scalar particles which arise from the spontaneous symmetry breaking of the Peccei-Quinn symmetry [16]. They were first predicted independently but almost simultaneously by Weinberg and Wilczek [19, 20]. We also consider the existence of axion like particles, with similar properties to axions but with the ALP mass and photon-ALP coupling $g_{a\gamma}$ as two independent parameters. These ALPs also make for good dark matter candidates [3]. The theoretical model of axions and ALPs predicts an oscillation between photon and ALP states in the presence of an external magnetic field [17]. The specific dynamics of this oscillation are dependent on the external magnetic field, the mass of the predicted axion/ALP, and its coupling to the photon field. Using these parameters, we are able to predict the photon-ALP oscillations which occur as photons propagate through astrophysical magnetic fields and toward our observatories. When creating these models, we expect to see a type of "wiggle" feature appearing in the spectra of VHE γ-ray sources such as M87, provided there are relatively strong magnetic fields along their line of sight. In the case of our source, the Virgo cluster surrounding it has been well studied and is known to have a relatively strong central magnetic field. More information on how we model and constrain the Virgo magnetic field can be found in our previous publication [6].

In summary, we use the gammaALPs (v0.3.0) [14] software package to generate 1000 pseudo-random realizations of the magnetic field for each set of parameter values. In [6], we constrain the central magnetic field of the Virgo galaxy cluster to 34.2 μG by modelling it with two distinct regions: an inner an outer region. We achieve this by comparing the Faraday Rotation measures along two lines of sight: to M87 at the center and M84 and the outer region. When modelling the magnetic field, we utilize a divergence free homogeneous and isotropic Gaussian turbulent magnetic field with zero mean and variance B^2 [15]. We assume that the power spectrum of the turbulence follows a power law with wave numbers, $M(k) \propto k^q$ between $k_L \leq k \leq k_H$ and otherwise zero [13]. Using this magnetic field we generate 1000 photon-ALP oscillation probabilities for M87. We span the mass-coupling parameter space of ALPs from mass m = 3.162 neV - 316.2 neV and coupling $g_{a\gamma} = 4.6 \times 10^{-12}$ GeV^{-1} - 10^{-10} GeV^{-1}. We divide each axis into 5 log-spaced bins and probe a total of $5 \times 5 = 25$ specific "pixels" along the parameter space to check for preferences for our ALP model(s). For each pixel, we are now presented with 1000 ALP models to fit against. We perform each fit individually and collect the likelihoods of each. We treat the results statistically and use the 5th quantile value of the C-stat distribution in each pixel to represent the likelihood of the ALP model in that specific pixel. We then assume this model to be a fair representation of the ALP models in that pixel and compare it against the no ALP case, which in this case is a log parabola with EBL attenuation. An example of this has been illustrated in Fig. 1.

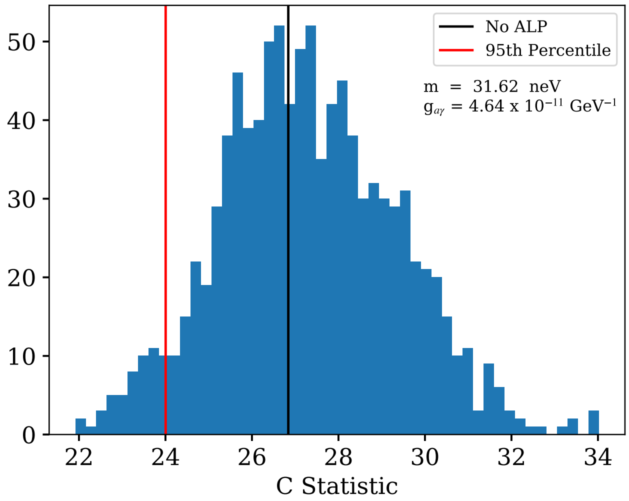

Figure 1: Histogram showing the likelihoods of the pseudo-random models of photon-ALP oscillation wiggles. This specific histogram shows our best case at a mass of 31.62 neV and a coupling of 4.64×10^{-11} GeV^{-1}.

After making these comparisons, we get a spread of variations from the no ALP model, with a preference seen in some cases. But even in the case of our most preferred pixel in the parameter space, we still only see a preference for the ALP model of $< 2\sigma$ with a ΔC-stat value of 2.84. Shown in the Fig. 2 is a comparison of the best case in our parameter space against the other 24 pixels as a difference in likelihood. Simultaneously, shown in Fig. 3 is a direct comparison of the Log Parabola with EBL model against one of our best case ALP models. Our results show a slight preference for the ALP model, but we do not have enough statistics to confidently separate the wiggles from statistical fluctuations.

6. Conclusions

In summary, we used different spectral models to select an optimal intrinsic spectrum of the source. We see a preference for a log parabola over a power law with a significance of 5.45 σ. This result in itself proves interesting because significant curvature in the VHE spectrum of M87 has not yet been observed. Using the log parabola as our best approximation for the intrinsic spectral shape, we further introduced an EBL model which could be freely scaled along its normalization. With few statistics above ~10 TeV, where the EBL attenuation kicks in for this source, placing constraints proves challenging, but we are able to place an upper limit on the normalization at $\alpha \leq 2.82$ with 95% confidence in our prediction. We fit our spectra against ALPs models across a 5×5 pixel parameter space of mass vs. coupling spanning ALPs from mass m = 3.162 neV - 316.2 neV and coupling $g_{a\gamma\gamma} = 4.6 \times 10^{-12}$ GeV^{-1} - 10^{-10} GeV^{-1}. The ALP models show a slight preference over the no ALPs model within certain pixels of our parameter sub-space, but this is below 2σ, which implies that we are unable to successfully separate a signal from the underlying statistical fluctuations. This highlights the necessity of high signal-to-noise ratio when searching

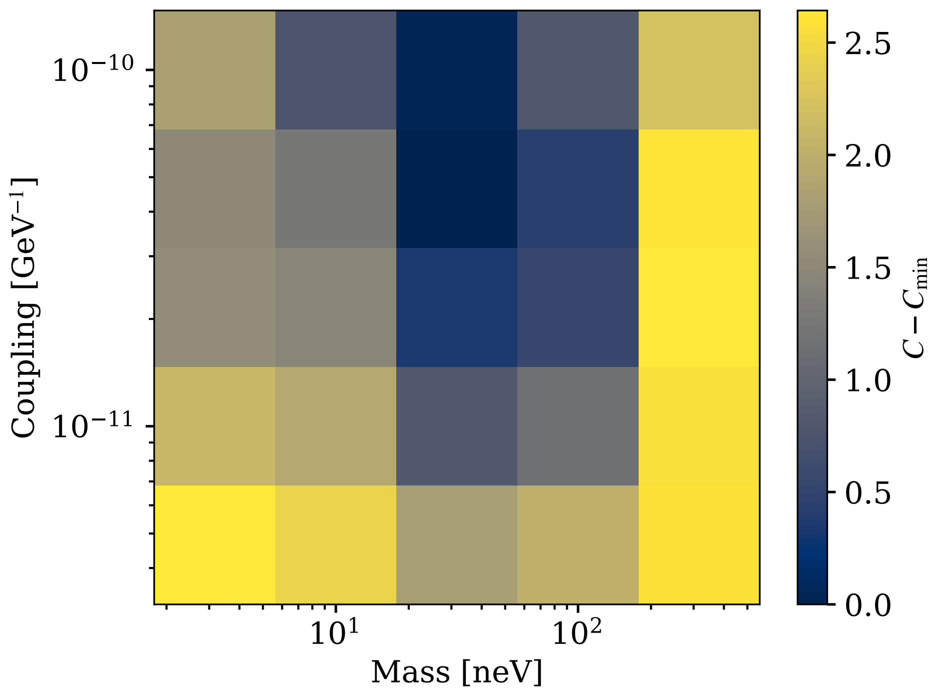

Figure 2: Illustration of the difference between our best case for the ALPs model and the other points in the parameter space. This illustrates the deviation of each pixel from the best case scenario.

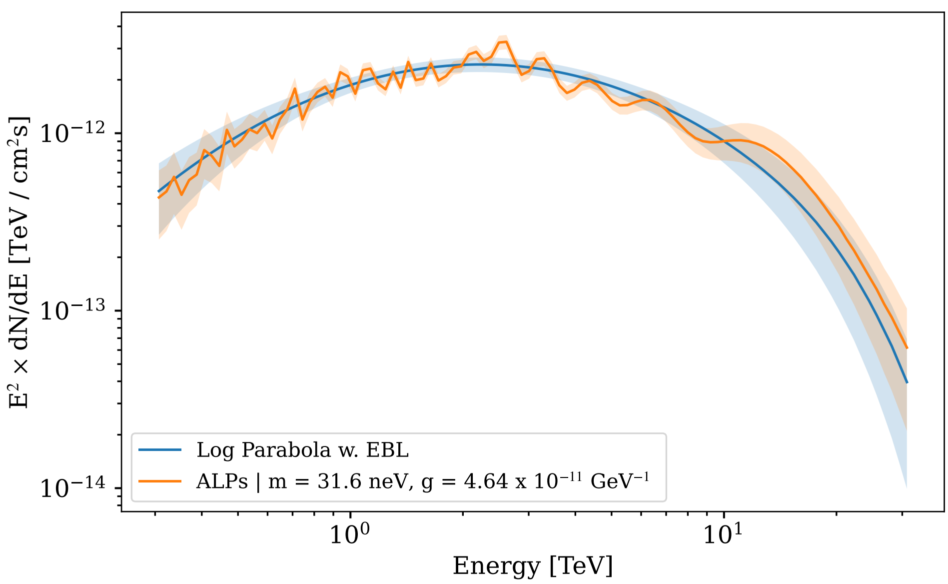

Figure 3: The best fit of the Log Parabola w. EBL model plotted along with the 5th quantile model of one of the best case pixels in the parameter space. Specifically at m = 31.62 neV and a coupling of 4.64×10^{-11} GeV^{-1}.

for ALP-induced spectral wiggles. We might be able to improve our constraints further by utilizing data from CTA provided we can observe M87 in flaring states using the observatory.

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