ALPs searches with LST-1

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Abstract. Axions and axion-like particles (ALPs) are hypothetical particles predicted by several extensions of the Standard Model and viable candidates for solving one of the big mysteries of the Universe: Dark Matter. By exploring the spectra of astrophysical objects obtained from observations with the Large Size Telescope (LST-1), we can search for signatures that such particles may leave. In particular, we look for oscillations in the spectra due to conversions between ALPs and very-high-energy (VHE) gamma rays. Our targets of interest include the blazars Mrk 421, Mrk 501, BL Lac, and 1ES1959+650, extensively observed with LST-1. The photon-ALP conversion probability is impacted by external magnetic fields, and for that reason, all magnetic fields in the propagation path need to be evaluated. In addition to the magnetic field in the relativistic jet of the blazar, we consider the impact of the Extragalactic Background Light in the intergalactic magnetic field and the magnetic field of the Milky Way for each source separately. For ALP masses in the neV range and magnetic field strengths of O(μG), these oscillations are more likely with photons in the GeV range, making LST-1 an optimal instrument for testing the ALP hypothesis in the VHE gamma-ray energy range. By exploring the LST-1 data of several blazars, our aim is to combine constraints from each source at the likelihood level, ultimately creating unique constraints in the ALP parameter space. These would be the first combined constraints obtained with a dataset from a group of blazar sources.

1 Introduction

The Standard Model of elementary particles has been under scrutiny ever since its creation. Longstanding issue of the Strong CP problem in the Quantum Chromodynamics has led to a postulation of a new family for particles, named axion-like particles (ALPs). This name was motivated by the solution of the Strong CP problem, a pseudo-Nambu-Goldstone boson called axion [1–3], which turned out to be quite similar to other particles emerging from similar theories beyond the Standard Model (see [4] for a review). An interest for these particles, aside from the fact that axion itself could solve the Strong CP problem, lays in their ability to constitute significantly large amount of Dark Matter [5].
Searches for these particles rely on an important property of ALPs; their interaction with

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photons through a two photon vertex (see [6] for a review of studies for ALPs with IACTs). Studies for axion and ALPs have been strongly motivated on wide range of energies, directly connected to the two principal properties of these particles; mass m_a and strength of their coupling to photons $g_{a\gamma}$. In cases where this coupling occurs in astrophysical magnetic fields, search for ALPs can be performed using the observations of very-high-energy gamma rays from astrophysical objects. In this work, we are analysing around 150 hrs of observations of 3 such objects, namely blazars Mrk 421, Mrk 501 and 1ES1959+650, observed with the Large-Sized Telescope (LST-1). LST-1 is the first prototype of the largest telescope of the upcoming Cherenkov Telescope Array Observatory (CTAO), located at the Observatory Roque de Los Muchachos, on Canary Island of La Palma [7]. Our study is based on search for irregularities in the spectra, caused by the photon-ALP interaction, and ultimately combining the constraints in the ALPs parameter space.

2 Spectral analysis and ALP modelling

The reconstruction of the photon flux observed from a source in a scenario where ALPs are expected to leave signatures in their observed spectrum requires several steps. First, the intrinsic photon flux, modelled by functions like power-law (PWL) and log-parabola (LP), arising from the underlying physics of particle acceleration and radiation mechanisms. In our study, the dataset from each source is analysed using the Bayesian blocks method [8] to optimise the dataset division into several groups based on the activity of the source, since they can be used individually for setting the exclusions in the ALPs parameter space [13]. Each of these spectra are then fitted to the best fit function (PWL or LP) and set as our null hypothesis, assuming no existence of ALPs.
The following step considers the ALPs photon survival probability, computed using the `GammaALPs` code for solving equations of motion of a photon-ALP system [1]. Given that the conversion of photons to ALPs and vice-versa occurs in magnetic fields, knowledge about the environments through which gamma-rays are travelling is crucial. To account for the properties of targets—AGNs with strong relativistic particle jets located in galaxy clusters characterised by weak magnetic fields, all at redshifts below $z = 0.1$—we compute the photon survival probability by considering mixing in the relativistic jet's magnetic field, EBL attenuation in the intergalactic magnetic field, and interactions with the Milky Way's magnetic field. For the magnetic field in the jet, we used the model composed of a helical, and tangled component, starting from the parabolic base and developing down the conical jet, developed by [9] and customised to each of our targets following the SED parametrisation by [10]. As of the EBL attenuation, we use the model by [12] and the regular component of the Milky Way magnetic field model by [11].

Finally, the expression for what we assume to be the observed flux in case of the existence of ALPs is:

$$\frac{d\Phi_{obs}}{dE} = \frac{d\Phi_{int}}{dE} \times P_{a\gamma}(E_\gamma; m_a, g_{a\gamma}, B, z), \tag{1}$$

where $d\Phi_{int}/dE$ is the intrinsic flux of the source fitted with a log-parabola function, E_γ is the energy of the gamma ray, and B is the external magnetic field through which the photon-ALP system is propagating.

Testing the ALPs models is performed using 100 pairs of mass and coupling, determined by the critical energy E_{crit} around which the conversion is expected to happen:

$$E_{crit} \sim 2.5 \text{ GeV } \frac{|m^2_{a,neV} - \omega^2_{pl,neV}|}{g_{11} B_{\mu G}}. \tag{2}$$

[1] https://gammaalps.readthedocs.io/en/latest/index.html

With the peak sensitivity in the GeV-TeV energy range, LST-1 allows to test the ALPs with masses of $m_a \sim$ neV and $m_a \sim 10^{-2}$ neV, respectively. As of the strength of coupling to photons, the tested range is bounded by upper limits set by CAST $g_{a\gamma} < 6.6 \times 10^{-10}$ GeV^{-1}, while the lower bound is set to 2×10^{-12} GeV^{-1}.

3 Statistical framework and preliminary results

The evaluation of the alternative hypotheses that assume the existence of ALPs is performed using the likelihood maximization method, similarly as in [13]. We define the likelihood as:

$$\mathcal{L}(m_a, g_{a\gamma}, \mu|D) = \prod_{i,k} \mathcal{L}_{i,k}(m_a, g_{a\gamma}, \mu_i|D_{i,k}), \tag{3}$$

where μ_i are the nuisance parameters coming from the fit function to the spectra for the i–th bayesian block in our dataset, and $D_{i,k}$ are the number of ON and OFF events observed in the k–th energy bin from the i–th bayesian block. For the test statistic, we use the likelihood ratio defined as:

$$\mathcal{TS}(g_{a\gamma}, m_a) = -2\Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(m_a, g_{a\gamma}, \hat{\mu}|D)}{\hat{\mathcal{L}}}, \tag{4}$$

where $\hat{\mathcal{L}}$ is the maximum value of the likelihood over the parameter space, while $\hat{\mu}$ are the parameters of the fit that maximize the likelihood for a given mass m_a and coupling $g_{a\gamma}$. Combination of the exclusion limits, obtained from each bayesian block dataset, is performed on the level of test statistic. The test statistic assigned to one particular model of ALPs for all different sources is summed and the confidence level for obtaining the exclusion regions is computed. To compute the coverage, we perform 100 Monte Carlo simulations of each source dataset and repeat the process to estimate the distribution of combined test statistic and derive the 95% and 99% confidence levels, further used to obtain the standard deviation σ. Preliminary constraints obtained from combining three out of seven blocks (in total) are shown in Fig 1.

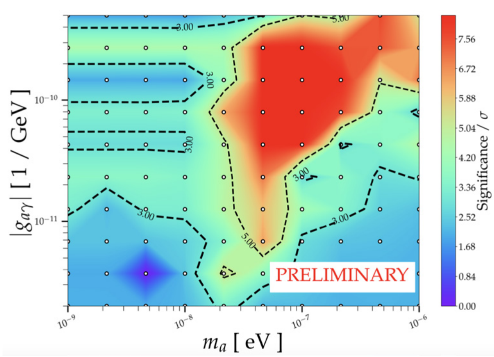

Figure 1. Prelimary constraints on the ALPs parameter space using a selected part of the LST-1 dataset of Mrk 421 and Mrk 501.

4 Next steps and future prospects

Next steps of this ongoing work are the addition and analysis of the remaining datasets (bayesian blocks), as well as the derivation of complete exclusion region using all the blocks

 https://doi.org/10.1051/epjconf/202531911003

from three sources in question; Mrk 421, Mrk 501 and 1ES1959+650. Up to now, we didn't include any systematical uncertainties on the spectral and magnetic field modelling, which will be addressed as the next step. Among the above-mentioned goals, our plan is to build a database for simplifying combination of data and creating future exclusions, storing the test statistics data from different datasets. In these files, we store all the relevant info about the source, observations, spectral modelling of the source flux, magnetic field modelling used to calculate the photon survival probability and finally the obtained test statistic. With the method for combining the test statistic from different datasets explained above, this database will enable obtaining the combined exclusions from the observations that might be of interest in the future.

Acknowledgements. We gratefully acknowledge financial support from the agencies and organizations listed here: https://www.ctao.org/for-scientists/library/acknowledgments/.

References

[1] R. D. Peccei and H. R. Quinn, *Constraints imposed by* CP *conservation in the presence of pseudoparticles*, Physical Review D **16**, 1791–1797 (1977). https://link.aps.org/doi/10.1103/PhysRevD.16.1791

[2] S. Weinbeg. *A New Light Boson?*, Physical Review Letters **40**, 223–226 (1978). https://link.aps.org/doi/10.1103/PhysRevLett.40.223

[3] F. Wilczek, *Problem of Strong P and T Invariance in the Presence of Instantons*, Physical Review Letters **40**, 279–282 (1978). https://link.aps.org/doi/10.1103/PhysRevLett.40.279

[4] J. Jaeckel and A. Ringwald, *The Low-Energy Frontier of Particle Physics* , Annual Review of Nuclear and Particle Science **20**, 4005–437 (2010)

[5] P. Arias et al., *WISPy cold dark matter*, Journal of Cosmology and Astroparticle Physics **6**, 013 (2012). https://ui.adsabs.harvard.edu/abs/2012JCAP...06..013A

[6] I. Batkovic et al.,*Axion-Like Particle Searches with IACTs*, Universe **7**, 185 (2021). https://www.mdpi.com/2218-1997/8/2/74

[7] H. Abe et al. (CTA-LST Project), *Observations of the Crab Nebula and Pulsar with the Large-Sized Telescope Prototype of the Cherenkov Telescope Array*, The Astrophysical Journal, **956**, 80 (2023). https://ui.adsabs.harvard.edu/abs/2023arXiv230612960P

[8] J. D. Scargle et al., *Studies in Astronomical Time Series Analysis. VI. Bayesian Block Representations*, The Astrophysical Journal **764**, 167 (2013). https://ui.adsabs.harvard.edu/abs/2013ApJ...764..167S

[9] J. Davies and M. Meyer and G. Cotter, *Relevance of jet magnetic field structure for blazar axionlike particle searches*, Physical Review D **103**, 023008 (2021). https://journals.aps.org/prd/abstract/10.1103/PhysRevD.103.023008

[10] W. J. Potter and G. Cotter, *New constraints on the structure and dynamics of black hole jets*, Monthly Notices of the Royal Astronomical Society **453**, 4070–4088 (2015). https://academic.oup.com/mnras/article/453/4/4070/2593637

[11] R. Jansson and G. R. Farrar, *The Galactic Magnetic Field*, The Astrophysical Journal Letters **761**, L11 (2012). https://ui.adsabs.harvard.edu/abs/2012ApJ...761L..11J

[12] A. Dominguez et al., *Extragalactic Background Light Inferred from AEGIS Galaxy SED-type Fractions*, Monthly Notices of the Royal Astronomical Society **410**, 2556 (2011). https://academic.oup.com/mnras/article/410/4/2556/1008012

[13] H. Abe et al. (MAGIC Collaboration), *Constraints on axion-like particles with the Perseus Galaxy Cluster with MAGIC*, Physics of the Dark Universe **44**, 101425 (2024). https://www.sciencedirect.com/science/article/pii/S2212686424000074