PROCEEDINGS OF SCIENCE

# Search for Axion-Like Particles with Observations of the Blazar Markarian 421 with VERITAS and Fermi-LAT

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Axion-like particles (ALPs) are light, pseudoscalar particles that are a beyond-the-standard-model generalization of the axion. Consequently, they are expected to couple to photons in external magnetic fields to compensate for spin difference. This coupling would induce modifications to the gamma-ray spectra of astrophysical sources, such as blazars, via ALP-photon oscillations in external fields near the source and in the Galactic magnetic field. In this contribution, we explore ALP-photon oscillation effects in the spectrum of the blazar Markarian 421. This work was performed using observations of an exceptional gamma-ray flare state from VERITAS and Fermi-LAT. Using these observations, we investigate constraints on the two parameters defining the ALP, namely its mass and coupling constant.

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## 1. Introduction

Axions are a consequence of the CP violating term added to the QCD Lagrangian in Peccei-Quinn theory as a proposed solution to the strong CP problem. In numerous theories beyond the standard model, including in string theory, generalized versions of the axion appear, termed "axion-like particles" (ALPs). ALPs are light, pseudoscalar particles, and like the axion, they are expected to couple to photons in the presence of an external transverse field component (e.g. a magnetic field), to necessarily compensate for the photon/ALP spin difference [1]. However, unlike with the axion, this coupling ($g_{a\gamma}$) is not related to mass ($m_a$) and thus, ALP parameters are significantly less theoretically constrained. Certain ranges of ALP mass and coupling strength have the potential to induce modifications to the gamma-ray spectra of astrophysical sources, such as blazars, via ALP-photon oscillations in external fields near the source and in the Galactic magnetic field. A unique consequence is that very-high-energy (VHE; > 100 GeV) gamma rays could circumvent annihilation with the extragalactic background light (EBL; see, e.g., [2]) by traversing cosmic distances as oscillated ALPs, leading to reduced opacity. In this work, we use gamma-ray data from VERITAS and Fermi-LAT of the great Markarian (Mrk) 421 flare of 2010 [3] to search for these signatures, and to set preliminary constraints on ALP mass and coupling constants. Numerous studies of this type have been pursued recently [4], including for this source [5].

## 2. Mrk 421 flare of 2010

Mrk 421 is a high synchrotron-peaked BL Lac (HBL) blazar located at a redshift of 0.031. During the month of February 2010, an extraordinary flare of ~ 27 Crab Units above 1 TeV was measured with the VERITAS observatory (Figure 1), the highest flux state for Mrk 421 ever observed in VHE gamma rays [3]. Fermi-LAT and VERITAS combined are sensitive in the energy range 0.1 GeV – 30 TeV, and favorably for this flare, exceptional data in the high-energy portion of the VERITAS spectrum was collected.

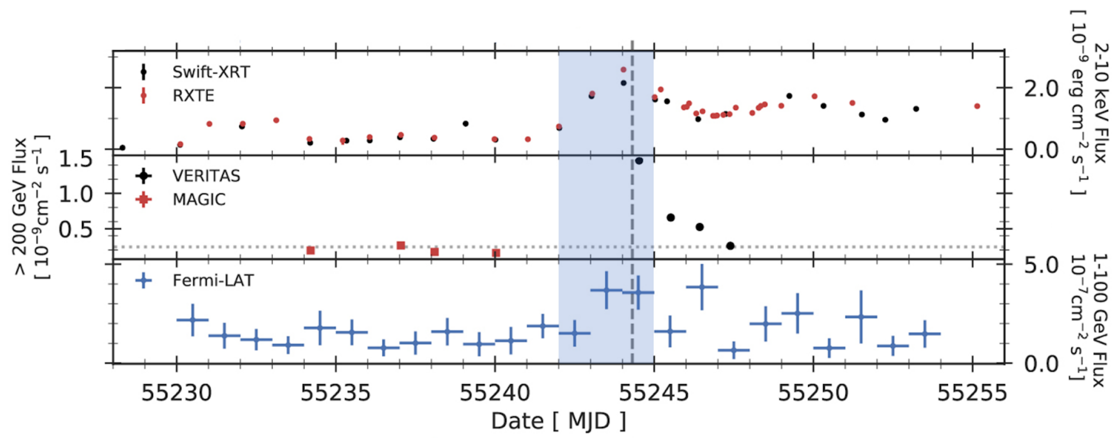


**Figure 1:** Mrk 421's 2010 flare as seen across several X-ray and gamma-ray instruments, adapted from [3]. The blue shaded date range is the time period selected for use in this study.

**Table 1:** Representative blazar jet parameters for Mrk 421 during the 2010 flare, from a one-zone synchrotron self-Compton model of Mrk 421 adopted for this flaring state by [11], used also in [5]. They are defined as follows: $r_{\rm VHE}$ is the distance of the VHE emission site to the central black hole in the jet frame, $B_0$ the magnetic field strength at $r_{\rm VHE}$, $\delta_{\rm D}$ the doppler factor, $n_0$ the electron density at $r_{\rm VHE}$, also in the jet frame, and $\theta_{\rm obs}$ the angle between the jet axis and the line of sight.

| $r_{\rm VHE}$ ($10^{17}$ cm) | $B_0$ (G) | $\delta_{\rm D}$ | $n_0$ ($10^3$ cm$^{-3}$) | $\theta_{\rm obs}$ (°) |
|---|---|---|---|---|
| 1 | 0.092 | 17 | 0.825 | 1.3 |

## 3. Data collection and methods

Flare data from both Fermi-LAT and VERITAS was pre-processed in their respective analysis packages [6, 7] and imported into the `gammapy` [8, 9] gamma-ray analysis package for a joint spectral analysis. The null hypothesis models the intrinsic spectrum ($\Phi_{int}$) as an exponentially cut-off power law, and includes EBL effects such that $\Phi_{obs,null}(E, z) = e^{-\tau(E,z)}\Phi_{int}(E)$, where $\tau(E, z)$ is the EBL optical depth from [2]. The ALP effect is naturally subject to the conditions at the source environment as well as the choice of $g_{a\gamma}$ and $m_a$. For the alternative hypothesis, the photon survival probability ($P_{\gamma\gamma}$), which includes both the ALP effect and the EBL attenuation, can be modelled using the `gammaALPs` [10] software package using the blazar jet parameters specified in Table 1, yielding $\Phi_{obs,null}(E, z) = P_{\gamma\gamma}\Phi_{int}(E)$.

## 4. Simulations and data analysis

Using `gammapy`, we fit the joint observed spectrum and obtain a WStat fit statistic $W = -2\log L$. The likelihood $L$ is defined to be

$$L\left(n_{\rm on}, n_{\rm off}, \alpha; \mu_{\rm sig}, \mu{\rm bkg}\right) = \frac{\left(\mu_{\rm sig} + \mu_{\rm bkg}\right)^{n_{\rm on}}}{n_{\rm on}!}\exp\left(-\left(\mu_{\rm sig} + \mu_{\rm bkg}\right)\right) \times \frac{\left(\mu_{\rm bkg}/\alpha\right)^{n_{\rm off}}}{n_{\rm off}!}\exp\left(-\mu_{\rm bkg}/\alpha\right)$$

where $n_{\rm on}$ is the number of counts in the on region, $n_{\rm off}$ is the number of counts in the background region, $\alpha$ is the ratio of acceptances in the on region to the off region, $\mu_{\rm sig}$ is the predicted signal counts, and $\mu_{\rm bkg}$ is the predicted background counts[1]. Following [5], in order to set exclusion regions on the ALP parameter space, a threshold value $W_{th}$ must be defined:

$$W_{th} = W_{min} + \Delta W \tag{1}$$

where $W_{min}$ is the minimum best-fit in the $m_a - g_{a\gamma}$ plane, and $\Delta W$ corresponds to a particular confidence level (CL). Given that the spectral modifications depend nonlinearly on the ALP parameters, we derive the value of $\Delta W$ from 400 event count simulations generated from the best-fit null hypothesis model with `fermipy` and `gammapy`. Here, we make the assumption that the probability distribution of the alternative hypothesis is approximated with the probability distribution of the null hypothesis [5, 12]. An example of fitting to simulated data is seen in Figure 2, and the $\Delta W$ can be derived from the $TS$ distribution shown in Figure 3, where $TS = W_{null} - \hat{W}_{w/ALPs}$ , and $W_{null}$ and $\hat{W}_{w/ALPs}$ are the fit statistics of the null and best fit ALP models respectively.

[1] https://docs.gammapy.org/dev/user-guide/stats/wstat_derivation.html

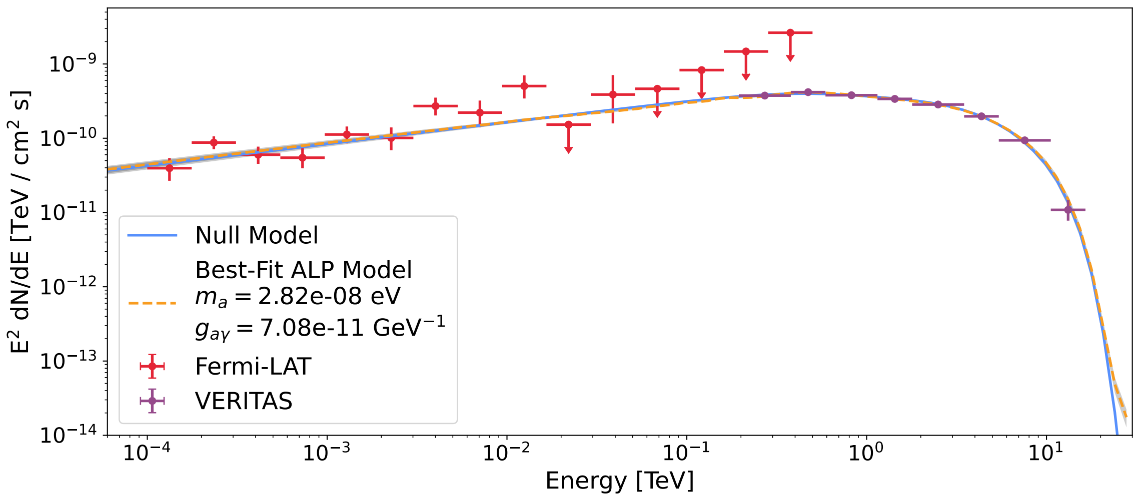


**Figure 2:** Best fit models with and without ALPs to simulated Fermi-LAT and VERITAS spectral data.

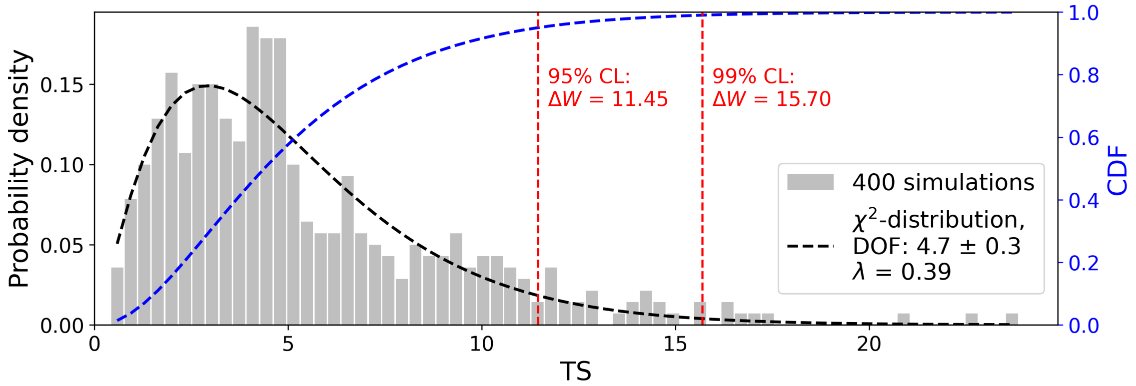


**Figure 3:** TS distribution for 400 simulated and analyzed datasets, fit by a non-central $\chi^2$ distribution with 4.7 degrees of freedom and a non-centrality parameter of 0.39. $\Delta W$ for the 95% and 99% confidence levels are extracted from the cumulative density function (CDF) of the fitted distribution.

## 5. Results

As shown in Figure 3, we find the 95% and 99% confidence level $\Delta W$ values to be 11.5 and 15.7 respectively. $W_{min}$ for the parameter space examined is found to be 37.6. Thus, using Equation 1, the 95% and 99% $W_{th}$ are determined to be 49.1 and 53.3 respectively. From these, we are able to preliminarily exclude certain regions of the $m_a - g_{a\gamma}$ space, as shown in Figure 4, where the 95% and 99% $W_{th}$ confidence levels discussed above have been traced out as contours. The 95% limits on axion-photon interactions set by CAST at $g_{a\gamma} < 0.66 \times 10^{-10}\text{GeV}^{-1}$ are also shown as a reference point, and may be easily compared to the figures shown in [13].

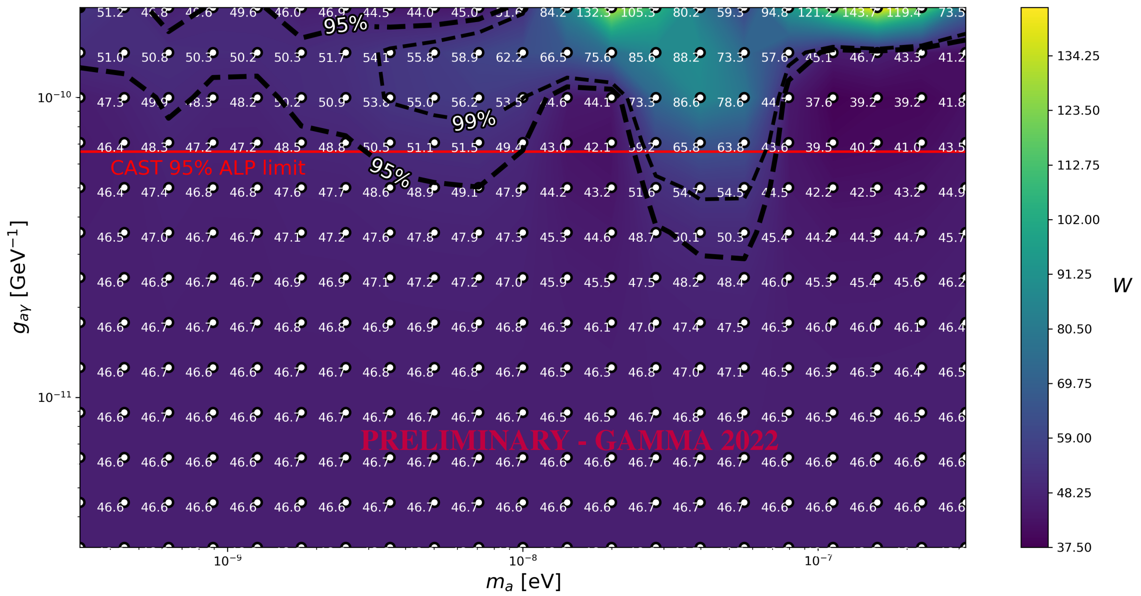


**Figure 4:** The $W$ fit statistic shown in $m_a - g_{a\gamma}$ space with the 95% and 99% CL contours demarcating the preliminary exclusion regions.

## 6. Summary

The extremely high flux state of Mrk 421's February 2010 flare makes this dataset potentially impactful. However, many sources of uncertainty affect this calculation, including the uncertainty of high energy flux points with VERITAS, uncertainty of EBL models in this energy range, and uncertainties in the magnetic field of the blazar jet. Until these can be properly considered in continued studies, these results must necessarily be considered preliminary. Nevertheless, we note that the preliminary results are consistent with the findings of previous analyses to date [13].

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