Searching for photon-ALPs mixing effects in AGN gamma-ray energy spectra

Qixin Yu and Dieter Horns

Institut für Experimentalphysik, University of Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
E-mail: qixin.yu@desy.de, dieter.horns@physik.uni-hamburg.de

Received August 11, 2022
Revised March 13, 2023
Accepted April 12, 2023
Published May 15, 2023

Abstract. High energy gamma-rays propagating in external magnetic fields may convert into axion-like particles (ALPs). In this case, the observed gamma-ray spectra are modified by the resulting energy-dependent conversion probability. In this study, we use the energy spectra of 20 extra-galactic gamma-ray sources recorded during 10 years of Fermi-LAT observations. We define a test statistics based upon the likelihood ratio to test the hypothesis for a spectral model without vs. a model with photon-ALPs coupling. The conversion probability is calculated for fixed values of the mass and two-photon coupling of the pseudo-scalar particle while the external magnetic field is characterized by the additional free parameters length scale $s$ and average field strength $B$. As a consistency check and in order to extend the analysis to include very high energy gamma-ray data, another test statistics is defined with the $\chi^2$ method. We find for 18 of the 20 sources a favorable fit, particularly for Markarian 421 and NGC 1275 a significant improvement, with the hypothesis of photon-ALPs coupling in likelihood analysis. The test statistics of the sources are combined and the significance has been estimated 5.3 $\sigma$ (test statistics summed in local maxima of all sources) and 6.0 $\sigma$ (global maxima). The significance is estimated from dedicated simulations under the null hypotheses. The locally best-fitting values of $B$ and $s$ fall into the range that is expected for large scale magnetic fields present in relevant astrophysical environments.

Keywords: gamma ray experiments, magnetic fields, Statistical sampling techniques

ArXiv ePrint: 2208.00079

https://doi.org/10.1088/1475-7516/2023/05/029
1 Introduction

Axions are pseudoscalars which are originally proposed as a solution to address the strong CP problem in quantum chromodynamics (QCD) [1, 2]. Besides the QCD axion, the existence of various axion-like particles (ALPs) has been predicted in the framework of extra-dimensional completions of the standard model [3–5]. ALPs are very light pseudo-scalar bosons (a) characterized mainly by a two-photon coupling \( g_{a\gamma\gamma} \) and its mass \( m_a \). Both, the QCD axion as well as ALPs are possible candidates for particle dark matter [6–9].

A non-vanishing coupling of ALPs to photons leads to a rich phenomenology for photon-ALPs mixing that can be observed in the universe and probed with laboratory experiments. While searches for axion/ALP type dark matter have so far only produced exclusion limits, astrophysical searches have been considered a promising approach to find signatures for photon-ALPs mixing in gamma-ray spectra [see e.g., 10–12]. There have been several claims for indications for anomalous TeV transparency [see e.g., 13–16] as well as modulation of spectra of Galactic sources [17]. In both cases, an interpretation of the observations has been put forward that singles out the mass range of \( 10^{-12} \text{GeV} < m_a < 10^{-10} \text{GeV} \) [17–19] where the uncertainties are mainly related to the assumption of the magnetic field present along the line of sight. The minimum value of the coupling would be accessible with the upcoming light-shining-through a wall experiment ALPS II [20].

The upper range of preferred coupling is in tension with the upper bounds of \( g_{a\gamma\gamma} < 6.6 \times 10^{-11} \text{GeV}^{-1} \) (95% c.l.) from the CAST experiment that searches for ALPs generated in
the core of the sun and then re-converts to X-ray photons in the transversal magnetic field of the CAST magnet [21]. However, the conversion inside the sun may be modified, effectively suppressing the ALPs flux emitted by the sun [22].

Here, we extend the search for spectral modulations in high energy and very high energy gamma-ray data of a sample of high frequency peaked BL Lac type objects (HBL) and the radio galaxy NGC 1275. Different from previous studies where a particular model for the magnetic field is used and the values of the axion-related parameters are left free, we instead assume a fixed mass \( m_a = 3.6 \text{ neV} \) and coupling \( g_{a\gamma\gamma} = 2.3 \times 10^{-10} \text{ GeV}^{-1} \) motivated by [17] and leave the constant magnetic field strength and its spatial extension as free parameters.

In the following sections, we present the calculation for the conversion probability in astrophysical magnetic fields (section 2), the source selection and reconstruction of energy spectra (section 3), and the results in section 4.

2 Photon-ALP oscillation model and astrophysical magnetic fields

The photon-ALP oscillation effect occurs in the presence of an external magnetic field. The photon-ALP coupling is described by the following Lagrangian [23]:

\[
\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a E \cdot B,
\]

where \( g_{a\gamma\gamma} \) is the coupling constant between ALPs and photons, \( a \) is the ALP field, \( F_{\mu\nu} \) is the electromagnetic field tensor, \( \tilde{F}^{\mu\nu} \) is its dual tensor. \( E \) and \( B \) are the electric and magnetic fields, respectively. Considering an initially polarized photon beam propagating through a single homogeneous magnetic field domain, the propagation equation can be written in a Schrödinger-like form:

\[
\left(i \frac{d}{dx_3} + E + \mathcal{M}\right)\Psi(x_3) = 0,
\]

with

\[
\Psi(x_3) = (A_1(x_3), A_2(x_3), a(x_3))^T,
\]

where \( A_1(x_3) \) and \( A_2(x_3) \) are the photon linear polarization states along \( x_1 \) and \( x_2 \) axis respectively, \( a(x_3) \) denotes the ALP state. \( \mathcal{M} \) represents the photon-ALP mixing matrix.

The mixing matrix could be simplified in the case where \( B \) is homogeneous. Here we use \( B_T \) the transverse magnetic field, and \( B_1 \) vanishes if \( B_T \) is chosen to be along the \( x_2 \) axis. We denote the photon polarization state parallel to the transverse magnetic field \( B_T \) direction by \( A_\parallel \), and the orthogonal one by \( A_\perp \). In this way \( \mathcal{M} \) can be simplified and written as [14, 24, 25]

\[
\mathcal{M} = \begin{pmatrix}
\Delta_\perp & 0 & 0 \\
0 & \Delta_\parallel & \Delta_{a\gamma} \\
0 & \Delta_{a\gamma} & \Delta_a
\end{pmatrix},
\]

where the terms \( \Delta_\perp \equiv \Delta_{\text{pl}} + \Delta_{\text{CM}} + \Delta_{\text{CMB}} \), \( \Delta_\parallel \equiv \Delta_{\text{pl}} + \Delta_{\text{CM}} + \Delta_{\text{CMB}} \), \( \Delta_{a\gamma} \equiv \frac{1}{2} g_{a\gamma\gamma} B_T \) and \( \Delta_a \equiv -\frac{m_a^2}{2E} [14, 23] \), where \( m_a \) is the mass of the ALP, \( \Delta_{\text{pl}} \) stands for plasma effects and has the form

\[
\Delta_{\text{pl}} \equiv -\frac{\omega_{\text{pl}}^2}{2E} \simeq -1.1 \times 10^{-10} \times \left(\frac{E}{\text{TeV}}\right)^{-1} \times \left(\frac{n_e}{10^{-3} \text{ cm}^{-3}}\right) \text{ kpc}^{-1},
\]
where \( \omega_{\text{pl}} = \sqrt{4\pi n_e e^2/m_e} \) is the plasma frequency and \( n_e \) is the electron density in the medium (typical value of \( n_e \) used here is \( 1.1 \times 10^{-2} \text{ cm}^{-3} \) [26]). The terms \( \Delta_{\text{CM}}^{\parallel,\perp} \) (Cotton-Mouton effect) are associated with the birefringence effects of the vacuum expected from the Euler-Heisenberg Lagrangian in the presence of transverse magnetic field, and the term \( \Delta_{\text{CMB}} \) accounts for photon-photon dispersion [27]. In the following, we neglect the effects of birefringence and photon-photon dispersion since they do not affect the energy range covered with \textit{Fermi}-LAT. We list the relevant parameters for numerical calculation [14]:

\[
\Delta a_\gamma \simeq 7.6 \times 10^{-2} \times \left( \frac{g_{a\gamma\gamma}}{5 \times 10^{-11} \text{ GeV}^{-1}} \right) \times \left( \frac{B_T}{\mu G} \right) \text{kpc}^{-1},
\]

(2.6)

\[
\Delta a \simeq -7.8 \times 10^{-3} \left( \frac{m_a}{10 \text{ neV}} \right)^2 \times \left( \frac{E}{\text{TeV}} \right)^{-1} \text{kpc}^{-1}.
\]

(2.7)

For the simplest case of a large-scale homogeneous magnetic field, the probability of a photon oscillating into an ALP (or vice versa) after traveling a distance \( s \) is

\[
p_{\gamma\rightarrow a} = 4\Delta^2 a_\gamma \sin^2 \left( \frac{s \Delta_{\text{osc}}}{2} \right),
\]

(2.8)

where the oscillation wave number \( \Delta_{\text{osc}} \) has the form

\[
\Delta_{\text{osc}} \equiv \sqrt{(\Delta a - \Delta_{\text{pl}})^2 + 4\Delta^2 a_\gamma}.
\]

(2.9)

Furthermore, it can be seen from eq. (2.8) that the photon-ALP mixing becomes maximal and energy-independent when \( E \gg E_c \) given by

\[
E_c \equiv \frac{E|\Delta a - \Delta_{\text{pl}}|}{2\Delta a_\gamma}.
\]

(2.10)

This is similar to the resonant case, where \( \Delta a = \Delta_{\text{pl}} \).

In order to take into account photon absorption, e.g., by interaction with a soft photon background field, the photon-ALP system is then described by a modified Schrödinger-like equation similar to eq. (2.2), and can be written as [13, 23, 27, 28]

\[
\left( i \frac{d}{dx_3} + E + M + iD \right) \Psi(x_3) = 0,
\]

(2.11)

with the additional matrix

\[
D = \begin{pmatrix}
C(x_3) & 0 & 0 \\
0 & C(x_3) & 0 \\
0 & 0 & 0
\end{pmatrix},
\]

with \( C(x_3) \) related to the optical depth \( \tau(x_3)/2 = \int_0^{x_3} C(x'_3)dx'_3 \).

The formal solution of eq. (2.11) is then given for an initial condition \( \Psi(0) \):

\[
\Psi(x_3) = \exp \left( -i \int_0^{x_3} \left( E + M - iD \right)dx'_3 \right) \Psi(0).
\]

(2.12)

Then, the surviving probability of the photon in photon-ALP system can be given by [13, 14]:

\[
p_{\gamma\gamma} = |A_1(x_3)|^2 + |A_2(x_3)|^2.
\]

(2.13)
This formalism can be readily extended to consider un-polarized initial states by introducing the density matrix formalism and a von-Neumann type equation instead of the Schrödinger-type equation (2.11) [23, 28]. As for the magnetic fields along the propagation of photon-ALP beam, we consider three distinct regions for conversion: the source and its vicinity, the intergalactic space, and the Milky Way. The magnetic field strength and structure present in the Milky Way is fairly well known via observations of Faraday-rotation measures, the polarization of the emission from aligned dust grains and more indirectly through the synchrotron emissivity of the interstellar medium. The magnetic field of intergalactic space is only constrained to be smaller than \( \approx nG \) [29] and not to be lower than \( \approx 10^{-16} \) \( G \) [30]. Finally, the magnetic field of the sources and their neighborhood is poorly known and may differ from source to source.

The photon-ALP mixing effect in the intergalactic magnetic field (IGMF) is neglected here, similar to previous studies [14]. In this case, the propagation can be separated into three regions. In the source region, we obtain the solution using eq. (2.12), neglecting absorption \( C = 0 \). In the IGMF, we do not consider the mixing, such that for the solution in eq. (2.12), we assume \( \mathcal{M} \approx 0 \). Finally, in the Milky Way, we neglect additional absorption (\( C \approx 0 \)) caused by local radiation fields.

The magnetic field of the source and its environment is characterized by a minimal set of parameters used here: the strength of the transversal magnetic field \( B \) and its characteristic coherence length \( s \). The conversion in the Milky Way is calculated using the model of the galactic magnetic field (GMF) from ref. [31] taking into account the line of sight of individual sources.

3 Source selection and data reduction

3.1 Source selection

The sensitivity for signatures of photon-ALPs conversion in high energy gamma-ray spectra is related to the uncertainties on the differential flux measurements. Conversely, the appearance of modulations in the gamma-ray spectra requires a sufficiently large conversion probability \( p_{\gamma \rightarrow a} \) (see eq. (2.8)). Large distances with a sizeably transverse magnetic field are favorable conditions to search for such modulations. While in the previous study by [17], Galactic pulsars were used, we extend the search to extra-galactic objects.

Almost all extra-galactic gamma-ray sources are associated with active galactic nuclei (AGN). In order to cover a large range of energies with AGN spectra, we select objects which have a hard gamma-ray spectrum and are sufficiently bright to measure the differential flux accurately. In order to collect our source sample, the following selection cuts are applied to the fourth Fermi-LAT source catalogue, 4FGL [32]:

1. Source type (association): AGN of BL Lac type.

2. Red shift: \( z \) known or constrained \( z < 0.5 \).

3. TeV association: in order to potentially extend to very high energies (VHE: \( E > 100 \) \( \text{GeV} \)), we require the sources to have an association to known VHE sources (TeV-CAT flag).

4. Hard spectrum: photon index is smaller than 2.

5. Signal-to-noise ratio: detection significance larger than 50 standard deviations.

6. Photon statistics: number of predicted photons (\( N_{\text{pred}} \)) should exceed 1600.
The 19 sources passing the selection cuts are listed in table 1. Additionally, we include one more source, a well-known and bright radio galaxy, NGC 1275. This source is located at the center of the Perseus galaxy cluster which most likely supports an extended [33] as well as a turbulent magnetic field [34]. This magnetized environment is favourable for photon-ALPs mixing and has already motivated several authors to search for spectral irregularities in the Fermi-LAT energy spectrum of NGC 1275 [16, 22, 35].

### 3.2 Fermi-LAT data reduction

In this study, we make use of 10 years of LAT data taken in the period from Aug. 4, 2008 to Aug. 4, 2018 in the energy range from 100 MeV to 500 GeV. We select events within a region of interest (ROI) defined as a cone centered on each source with a half-opening angle of 10°.

The events are selected by applying a zenith cut of 90° to minimize the $\gamma$-ray contributions from the Earth’s limb. We set the spatial bin size to be 0.1° and distribute 48 energy bins (corresponds to 13 bins per decade) within the selected energy range for performing a binned likelihood analysis. Following the recommendations of the LAT instrument team, the energy dispersion is corrected by introducing 3 additional bins beyond the energy range analysed.

| AGN name      | Source type | $l$ [$^\circ$] | $b$ [$^\circ$] | $z$ | Detection signif. ($\sigma$) | Photon index | $N_{\text{pred}}$ |
|---------------|-------------|---------------|---------------|-----|-----------------------------|--------------|------------------|
| 1ES 0033+595  | HBL         | 120.90        | -3.02         | 0.467 | 68                         | 1.765        | 2954             |
| 3C 66A        | HBL         | 140.15        | -16.76        | 0.34  | 182                        | 1.971        | 15207            |
| PKS 0301-243  | HBL         | 214.63        | -60.19        | 0.2657 | 108                      | 1.914        | 5623             |
| NGC 1275      | Radio Galaxy| 150.58        | -13.26        | 0.017559 | 245                  | 2.114        | 35561            |
| PKS 0447-439  | HBL         | 248.81        | -39.91        | 0.343  | 167                        | 1.865        | 12536            |
| 1ES 0502+675  | HBL         | 143.79        | 15.89         | 0.34  | 64                         | 1.601        | 1718             |
| 1ES 0806+524  | HBL         | 166.25        | 32.94         | 0.138  | 100                        | 1.881        | 5147             |
| 1ES 1011+496  | HBL         | 165.53        | 52.71         | 0.212  | 169                        | 1.838        | 9806             |
| Markarian 421 | HBL         | 179.88        | 65.01         | 0.031  | 344                        | 1.781        | 30562            |
| Markarian 180 | HBL         | 131.91        | 45.64         | 0.045  | 50                         | 1.798        | 1623             |
| 1ES 1215+303  | HBL         | 189.01        | 82.05         | 0.131  | 146                        | 1.933        | 10779            |
| 1ES 1218+304  | HBL         | 182.21        | 82.74         | 0.182  | 83                         | 1.722        | 3285             |
| PKS 1440-389  | HBL         | 325.65        | 18.71         | 0.1385 | 78                         | 1.845        | 3788             |
| PG 1553+113   | HBL         | 21.92         | 43.96         | $\lesssim$ 0.5 | 120                  | 1.681        | 10046            |
| Markarian 501 | HBL         | 63.60         | 38.86         | 0.034  | 173                        | 1.790        | 11127            |
| 1ES 1727+502  | HBL         | 77.07         | 33.54         | 0.055  | 60                         | 1.790        | 2251             |
| 1ES 1959+650  | HBL         | 98.00         | 17.67         | 0.048  | 169                        | 1.817        | 11700            |
| PKS 2005-489  | HBL         | 350.37        | -32.61        | 0.071  | 70                         | 1.838        | 3115             |
| PKS 2155-304  | HBL         | 17.74         | -52.25        | 0.116  | 239                        | 1.850        | 17766            |
| 1ES 2344+514  | HBL         | 112.89        | -9.90         | 0.044  | 71                         | 1.811        | 3201             |

**Table 1.** AGN sources selected for this study (in order of right ascension). The information listed are Galactic longitude ($l$) and latitude ($b$), red shift ($z$). Also, detection significance, photon index, and predicted event counts from Fermi 4FGL catalog.
The LAT data processed in pass 8 (release 3, version 2) have been downloaded together with the spacecraft file and the matching instrumental response files (P8R3_SOURCE_V2 IRFs) from the Fermi Science Data Center. Subsequently, the events of class source with conversion in front and back part of the tracker are selected. The preparatory steps of the data analysis include creation of live time cube, data cubes etc. These tasks have been carried out using the Fermi Science Tools ver1.2.23\(^1\) [36]. Most of these steps of the data reduction have been conveniently performed with the python based fermipy ver0.19.0\(^2\) interface.

The diffuse backgrounds are modeled with pre-processed templates of the Galactic diffuse emission, gll_iem_v07.fits, and the extra-galactic isotropic radiation, iso_P8R3_SOURCE_V2_v1.txt. The energy dispersion for the background templates is already taken into account.\(^3\) Point sources from the Fermi-LAT fourth catalog (4FGL, [37]), within a region of 15\(^\circ\), are included to the source model.

The resulting energy spectra are displayed as spectral energy distributions (SEDs). The SEDs are derived by taking the differential flux measurements and multiplying the individual flux values in each bin by the squared geometrical mean energy of the bin.

4 Analysis and results

4.1 Spectral models

The energy spectra of the sources listed in table 1 are compared with two different models that follow from the two hypotheses considered here. The hypothesis \(H_0(ALPS)\) “without” photon-ALPs mixing is the null hypothesis and the alternative is \(H_1(ALPS)\) “with” photon-ALPs mixing.

In our spectral analysis, the intrinsic model of any AGN is either described by the Logparabola model or in a few cases by a single PowerLaw, as given in eqs. (4.1) and (4.2) respectively.

\[
\frac{dN}{dE}_{\text{intr.}} = N_0 \left(\frac{E}{E_b}\right)^{-\alpha} \left(\frac{E}{E_b}\right)^{-\alpha + \beta \ln(E/E_b)},
\]

where the free parameters \(N_0\) is the normalization factor at scale energy \(E_b\), which is usually held constant, \(\alpha\) is the power-law index and \(\beta\) the curvature parameter.

\[
\frac{dN}{dE}_{\text{intr.}} = N_0 \left(\frac{E}{E_b}\right)^{-\alpha},
\]

The choice of the spectral model is based upon the LAT 8-year source catalog (4FGL) [37].

The intrinsic spectrum is subsequently modified by absorption via pair-production on the soft extra-galactic background light (EBL). The optical depth \(\tau_{\gamma\gamma}(E)\) relies on the choice of an EBL model. Since the optical depth in the energy and red shift range considered here is small (\(\tau_{\gamma\gamma} \ll 1\)), the actual choice of the model is not of importance for the results obtained here, but needs to be included. The model of [38] is used as it is conveniently integrated in the PhotonALPsConv package.\(^4\)

Under the alternative hypothesis \(H_1\) with photon-ALP mixing, the spectrum is multiplied with the photon surviving probability \(p_{\gamma\gamma}\). It is a function of photon energy \(E\), ALP

\(^1\)https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/.
\(^2\)https://fermipy.readthedocs.io/en/latest/.
\(^3\)https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/.
\(^4\)https://github.com/me-manu/PhotALPsConv.
mass $m_a$, photon-ALP coupling $g_{a\gamma\gamma}$, transversal (constant) B-field strength $B$ and the distance $s$ over which the B-field is present.

In order to make the general problem of estimating the free parameters numerically tractable, we consider $m_a$ and $g_{a\gamma\gamma}$ fixed at values which have been found to be favorable to explain spectral modulations present in energy spectra of Galactic pulsars [17]. The resulting best estimates have been found to be $m_a = 3.6\text{ neV}$, $g_{a\gamma\gamma} = 2.3 \times 10^{-10}\text{ GeV}^{-1}$.

Therefore, the spectra modeled in this way for the two hypotheses (with and without photon-ALP conversion) would have the following forms:

\[
H_0 : \left( \frac{dN}{dE} \right)_{\text{w/o ALP}} = e^{-\tau_{\gamma\gamma}} \left( \frac{dN}{dE} \right)_{\text{intr.}},
\]

and

\[
H_1 : \left( \frac{dN}{dE} \right)_{\text{w/ALP}} = \left( \frac{dN}{dE} \right)_{\text{intr.}} p_{\gamma\gamma}(E, m_a, g_{a\gamma\gamma}, B, s),
\]

respectively, where $(dN/dE)_{\text{intr.}}$ is the source model referring to eq. (4.1) or eq. (4.2), and photon survival probability $p_{\gamma\gamma}$ in eq. (4.4) is calculated with eq. (2.13).

### 4.2 Parameter estimates: null hypothesis

We fit the experimental data with two different approaches using as test statistics separately the log likelihood ratio and $\Delta \chi^2$. For the likelihood fitting of the SED we use the forward-folding method as implemented in the fermitools. This way, we determine the likelihood value for the best-fitting model for both hypotheses $H_0$ and $H_1$. The effect of the survival probability $p_{\gamma\gamma}$ is implemented by calling the `gtlike` tool with a so-called `filefunction` model. For each value of $B$ and $s$ chosen, we optimize the parameters of $(dN/dE)_{\text{intr.}}$ using the likelihood fitting method.

In order to check for consistency and to be more flexible to include additional data sets (e.g. VHE spectra), we also implement a $\chi^2$ fitting method with the definition for the Fermi-LAT data

\[
\chi^2 = \sum_{i=1}^{N} \frac{(D_{ij}\Psi_j - \phi_i)^2}{\sigma_i^2},
\]

where $N$ is the number of energy bins ($N = 18$ for all sources analyzed with $\chi^2$ method), $D_{ij}\Psi_j$ and $\phi_i$ are respectively the expected and observed $\gamma$-ray flux in bin $i$ with a statistical uncertainty $\sigma_i$. The model flux $\Psi_j$ is corrected using the energy dispersion matrix $D_{ij}$ determined for the particular observation using the tool `gtdrm` with one additional bin added to the lower and upper end of the spectrum.\(^5\)

In table 2, we list the best-fitting parameters estimated under the null hypothesis with the likelihood method (for $\chi^2$ estimates, see table 5 in appendix A). For each source, we find a maximum likelihood $L_{\text{max}}^0$ (resp. a minimum $\chi^2_{\alpha/\alpha\text{ALP}}$) with the best-fitting normalization value $N_0$, the power-law index $\alpha$, the curvature parameter $\beta$ and the scaling energy $E_b$. The uncertainties listed are calculated for a 68% confidence interval.

### 4.3 Parameter estimates: ALPs hypothesis

The alternative ($H_1$) hypothesis with photon-ALPs mixing includes two additional free parameters which relate to the strength $B$ of the magnetic field and the distance $s$ over which

\(^5\)https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_edisp_usage.html.
and to include the best-fitting parameters of from eq. (4.3), where sources with no curvature parameter are modeled with Table 2. Best-fitting parameters for null hypothesis with likelihood method using the modeled spectra from eq. (4.3), where sources with no curvature parameter are modeled with PowerLaw, and the rest is with Logparabola. The normalization is given in units of $10^{-12}$ MeV$^{-1}$ cm$^{-2}$ s$^{-1}$. The estimated uncertainties ($\sigma$) are listed as well (except for the scaling energy $E_b$ which is kept fixed at the value from the catalogue).

| AGN name        | $N_0$          | $\alpha$       | $\beta$ | $E_b$ [MeV] |
|-----------------|----------------|----------------|---------|-------------|
| 1ES 0033+595    | 0.363(0.015)   | 1.68(0.03)     | $-4(12)$ | 3177        |
| 3C 66A          | 10.9(0.1)      | 1.88(0.01)     | 39(4)   | 1211        |
| PKS 0301-243    | 5.66(0.12)     | 1.83(0.02)     | 31(8)   | 954.4       |
| NGC 1275        | 56.1(0.4)      | 2.04(0.004)    | 60(3)   | 883.6       |
| PKS 0447-439    | 4.62(0.07)     | 1.74(0.01)     | 52(5)   | 1605        |
| 1ES 0502+675    | 0.0593(0.0026) | 1.48(0.03)     | –       | 6322        |
| 1ES 0806+524    | 2.31(0.06)     | 1.80(0.02)     | 26(8)   | 1297        |
| 1ES 1011+496    | 7.6(0.1)       | 1.75(0.01)     | 33(5)   | 1066        |
| Markarian 421   | 18.0(0.1)      | 1.73(0.005)    | 19(2)   | 1286        |
| Markarian 180   | 0.164(0.008)   | 1.77(0.03)     | –       | 2679        |
| 1ES 1215+303    | 9.04(0.14)     | 1.84(0.01)     | 44(5)   | 1066        |
| 1ES 1218+304    | 0.215(0.007)   | 1.69(0.02)     | –       | 4442        |
| PKS 1440-389    | 1.01(0.03)     | 1.70(0.03)     | 56(11)  | 2014        |
| PG 1553+113     | 3.93(0.06)     | 1.56(0.01)     | 38(5)   | 1847        |
| Markarian 501   | 4.57(0.07)     | 1.70(0.01)     | 17(4)   | 1478        |
| 1ES 1727+502    | 0.202(0.008)   | 1.75(0.03)     | –       | 3005        |
| 1ES 1959+650    | 3.22(0.05)     | 1.76(0.01)     | 23(5)   | 1733        |
| PKS 2005-489    | 0.526(0.016)   | 1.80(0.02)     | –       | 2398        |
| PKS 2155-304    | 15.4(0.2)      | 1.77(0.01)     | 35(3)   | 1136        |
| 1ES 2344+514    | 0.807(0.03)    | 1.73(0.03)     | 50(12)  | 1938        |

Table 2. Best-fitting parameters for null hypothesis with likelihood method using the modeled spectra from eq. (4.3), where sources with no curvature parameter are modeled with PowerLaw, and the rest is with Logparabola. The normalization is given in units of $10^{-12}$ MeV$^{-1}$ cm$^{-2}$ s$^{-1}$. The estimated uncertainties ($\sigma$) are listed as well (except for the scaling energy $E_b$ which is kept fixed at the value from the catalogue).

the photons can mix in the constant external magnetic field. For each pair of $B$, $s$, we maximize the likelihood $L_{\text{max}}^1$ (or minimize $\chi^2_{\text{w/ALP}}$). We carry out this procedure for a discrete set of pairs of $B$ and $s$ located on a logarithmic grid with (150 × 150) steps where $10^{-3} \mu G \leq B \leq 1 \mu G - 10^3 \mu G$ and $10^{-2}\text{ kpc} \leq s \leq 10^3\text{ kpc} - 10^4\text{ kpc}$. Units!! The ranges are chosen such that the critical energy $E_c$ could fall into the analyzed energy range, and to include the best-fitting parameters of $(B,s)$ under the $H_1$ hypothesis. In case of multiple local maxima found, we choose the combination which minimizes the total energy present in the magnetic field given by $\propto s^3B^2$. The same criterion is used for the grid with the $\chi^2$ values.

In order to test the significance of the alternative hypothesis against the null hypothesis, we introduce the test statistics (TS) based upon the likelihood ratio:

$$TS(B, s) = -2 \times (\ln(L_{\text{max}}^0) - \ln(L_{\text{max}}^1(B, s))).$$  \hfill (4.6)
Figure 1. Left panel: $(B, s)$ grid map where the color bar indicates the test statistics $TS$ which is twice the difference of log-likelihood values between null and ALP hypotheses. Right panel: $(B, s)$ grid map where the color bar indicates the difference of $\chi^2$ values fitted in null and ALP hypotheses. The black and white marker correspond to the local and global best-fitting parameters respectively.

For example, in the left panel of figure 1 (for figures of other sources see figures 10–27 in appendix A) we show the resulting values of $TS(B, s)$ on the grid for Markarian 421 (Mkn 421).

The value of the TS varies in a characteristic way for different values of $B$ and $s$. For small values of $B$ and $s$, the two hypotheses are not distinguishable as the survival probability $p_{\gamma \rightarrow a}$ is too small in comparison with the measurement uncertainties. For high values of $B$ and $s$ a large part of the parameter space is excluded. Notably, a repetitive pattern of local maxima occurs which are aligned along increasing values of $B$ and $s$. The local maxima correspond to the case where $s \cdot \Delta_{\text{osc}} > 2\pi$ and therefore multiple oscillations occur. For increasing values of $B$, the critical energy $E_{\text{crit}}$ decreases therefore, a wider part of the energy spectrum is affected.

On the search grid, we locate the global maximum of $TS(\hat{B}, \hat{s}) = 18.5$ for $\hat{B} = 21.0 \text{nG}$ and $\hat{s} = 216.4 \text{kpc}$ (see table 8 in appendix A for global maxima of other sources), which is marked with a white triangle error bar. In this particular case, the global maximum $(\hat{B}, \hat{s})$ is located at a local maximum which corresponds to the parameters with the smallest value of $B^2 \cdot s^3$ which is proportional to the total energy required to build up the magnetic field.

We mark down the chosen local maximum $TS(\hat{B}_0, \hat{s}_0)$ with the smallest value of $B^2 \cdot s^3$, which in this case is identical with the global best-fitting results, and is shown as a black point error bar in figure 1.

In a consistent way, we obtain the best-fitting parameters for $(\hat{B}_0, \hat{s}_0)$ of chosen local maxima under the ALP hypothesis for the remaining sources listed in table 3.

Similar to the approach used for the $TS$ defined by the likelihood ratio,

$$
\Delta \chi^2 = \chi^2_{\text{w/o ALP}} - \chi^2_{\text{w/ALP}},
$$

is also calculated for the same grid and the best-fitting parameters which maximise the $\Delta \chi^2$ are obtained. As an example, the right panel of figure 1 shows the corresponding grid of $\Delta \chi^2$ values. When comparing the $\Delta \chi^2$ values on the same grid as the $TS$ values, the same

---

6Note, the definition of $\Delta \chi^2$ and the sign is chosen such that we can use comparable value of $\Delta \chi^2$ and $TS$. 

---
patterns emerge and similar best-fitting values for \((\hat{B}, \hat{s})\) are found, as well as the values for \((\hat{B}_0, \hat{s}_0)\). There are however some differences which relate to the fact that the \(\Delta\chi^2\) method is based upon a coarser binning of the energy spectra and therefore the oscillation features remain in some cases under-sampled. In the same way, we have obtained the best-fitting combinations of \((\hat{B}, \hat{s})\) and \((\hat{B}_0, \hat{s}_0)\) from the \(\chi^2\) fit which are listed in tables 6 and 7 (in appendix A) respectively.

The best-fitting distance \(\hat{s}_0\) range from \(\approx 0.1\) kpc (1ES 1218+304) up to \(\approx 262\) kpc (Markarian 180). The bulk of the source spectra favor a conversion within a distance range of 1 kpc to 200 kpc with a magnetic field strength between 10 nG and 10 \(\mu\)G.

As an illustration of the best-fitting SED for the two hypotheses, we show in figure 2, the observed SED data points of Mkn 421 (see figures 28–45 in appendix A for other sources) together with the model curves. In the left panel, the SED data points are calculated with the likelihood binning while in the right figure, the SED points are calculated for a coarser binning. The best-fitting curve for the null hypothesis is shown as a green dashed line and is for both fitting methods very similar. For the case of photon-ALPs mixing, the resulting conversion probability leads to modifications of the spectrum mainly between 50 GeV and 500 GeV (shown as blue solid line). The relative amplitude of the modulation is about 15%.

| AGN name         | \(N_0\)         | \(\alpha\)       | \(\beta\) \(\times 10^{-3}\) | \(E_b\) [MeV] | \(\hat{B}_0\) [nG] | \(\hat{s}_0\) [kpc] |
|------------------|-----------------|------------------|-----------------------------|--------------|---------------|---------------------|
| 1ES 0033+595     | 0.593(0.023)    | 1.54(0.03)       | 36(12)                      | 3177         | 54.9 (27.9)   | 81.8 (28.4)         |
| 3C 66A           | 12.5(0.2)       | 1.80(0.01)       | 43(6)                       | 1211         | 322.7 (46.1)  | 7.2 (0.9)           |
| PKS 0301-243     | 10.4(2.8)       | 1.78(0.05)       | 41(10)                      | 954.4        | 24396.3(7912.3)| 0.2 (0.1)           |
| NGC 1275         | 103(5)          | 1.99(0.01)       | 82(3)                       | 883.6        | 26286.2(1142.6)| 0.2 (0.01)          |
| PKS 0447-439     | 7.20(0.14)      | 1.55(0.01)       | 87(6)                       | 1605         | 1675.6 (157.3)| 2.0 (0.1)           |
| 1ES 0502+675     | 0.0731(0.0047)  | 1.49(0.03)       | –                           | 6322         | 820.5 (74.1)  | 12.2 (0.7)          |
| 1ES 0806+524     | 2.32(0.06)      | 1.78(0.02)       | 11(10)                      | 1297         | 143.8 (21.2)  | 43.5 (3.8)          |
| 1ES 1011+496     | 7.67(0.12)      | 1.75(0.01)       | 25(6)                       | 1066         | 27.1 (5.7)    | 206.2(24.1)         |
| Markarian 421    | 19.1(0.2)       | 1.69(0.005)      | 13(2)                       | 1286         | 21.0 (4.1)    | 216.4 (18.4)        |
| Markarian 180    | 0.177(0.008)    | 1.72(0.03)       | –                           | 2679         | 16.7 (11.9)   | 262.8 (84.4)        |
| 1ES 1215+303     | 17.1(3.0)       | 1.77(0.06)       | 61(5)                       | 1066         | 18574.9 (4545.8)| 0.3(0.1)            |
| 1ES 1218+304     | 0.426(0.015)    | 1.69(0.02)       | –                           | 4442         | 32031.9 (7981.4)| 0.1(0.04)           |
| PKS 1440-389     | 1.76(0.09)      | 1.50(0.03)       | 105(12)                     | 2014         | 2013.3 (629.7)| 2.2 (0.4)           |
| PG 1553+113      | 4.96(0.10)      | 1.44(0.01)       | 43(6)                       | 1847         | 846.0 (36.5)  | 11.1 (0.3)          |
| Markarian 501    | 7.88(1.40)      | 1.67(0.02)       | 24(4)                       | 1478         | 29047.0 (7747.1)| 0.2(0.03)           |
| 1ES 1727+502     | 0.260(0.012)    | 1.72(0.02)       | –                           | 3005         | 1987.1 (65.4) | 9.3 (0.2)           |
| 1ES 1959+650     | 3.41(0.06)      | 1.71(0.01)       | 15(6)                       | 1733         | 63.8 (29.5)   | 29.6 (8.1)          |
| PKS 2005-489     | 0.707(0.048)    | 1.73(0.02)       | –                           | 2398         | 6400.6 (374.4)| 1.6 (0.1)           |
| PKS 2155-304     | 30.8(0.3)       | 1.76(0.01)       | 42(3)                       | 1136         | 30099.3 (6113.0)| 0.1(0.01)           |
| 1ES 2344+514     | 0.870(0.037)    | 1.62(0.04)       | 33(16)                      | 1938         | 244.2 (71.1)  | 15.0 (2.9)          |

Table 3. Best-fitting parameters of local maxima for ALP hypothesis with likelihood method using the modeled spectra from eq. (4.4). \(B\) and \(s\) are additional free parameters relating to the strength and length scale for the external magnetic field that is responsible for photo-ALP mixing effects. The normalisation is given in units of \(10^{-12} \text{MeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\). Parameters uncertainties (1\(\sigma\)) are included.
4.4 Hypotheses testing for the joined \textit{Fermi}-LAT spectra

The hypotheses testing is performed first on the individual energy spectra and subsequently in a
analysis of the joined test statistics of all spectra.

For either rejection or acceptance of null hypothesis, we estimate the distribution of $TS$ under
the null hypothesis following a similar procedure as described in [35]. We generate as
pseudoexperiments (PE) 400 sets of simulated gamma-ray spectra for each source under the
null hypothesis. The simulation of PE data sets is done through Gaussian sampling of the
expected event numbers in a counts cube generated for the gamma-ray sources and diffuse
emission present in the region of interest [36]. The resulting sim data sets are then subject
to the same data analysis procedure as outlined above. For each source, this results in two
distributions with 400 values of $TS$ according to eq. (4.6) and $\Delta \chi^2$ as defined in eq. (4.7),
respectively.

In the case of nested hypotheses the distribution of the test statistic should asymptotically
approach a $\chi^2$ distribution (in this case a non-central $\chi^2$ distribution under null
hypothesis) if the number of simulations is sufficiently high [39].

As an example, we present in figure 3 the distributions of $TS$ for Mkn 421 with likelihood
ratio test. The TS distribution is best approximated with a non-central $\chi^2$ distribution
(NCD) with about 0 degree of freedom ($df$) and non-centrality ($nc$) parameter $nc = 19.11$.
With the accumulated NCD, we derive the probability to find a value of $TS$ larger than the
one found in data ($TS = 18.5$) to be $p(TS > 18.5; df = 0.00, nc = 19.11) = 2.79 \times 10^{-4}$,
corresponding to a significance level of 3.6 $\sigma$. The result on Mkn 421 for the $\chi^2$ fit is slightly
less significant with $p(\Delta \chi^2 > 13.3; df = 4.38, nc = 9.82) = 7.39 \times 10^{-3}$, corresponding to a
significance level of 2.7 $\sigma$. Upon closer inspection, the binning for the $\chi^2$-fit is under-sampling
the modulation predicted for the spectrum when photon-ALPs oscillation is considered. We
can conclude from both tests, that in this case, the photon-ALP hypothesis is preferred over
the null hypothesis.
Figure 3. Left panel: simulated null distribution for Mrk 421 from likelihood ratio test. Right panel: simulated null distribution from $\Delta \chi^2$ test for the same source. The black dashed line indicates a fit to the distribution with a non-central $\chi^2$ function. The red solid line represents the resulting cumulative distribution function (CDF). The TS($\Delta \chi^2$) value derived from the local maxima of original data is marked as a blue (dot-dash) vertical line, while the TS($\Delta \chi^2$) value obtained from the global maxima is marked as a gray dotted line (in this case, the blue line coincides with the gray line).

The goodness of fit for the hypothesis $H_1$ is acceptable for 12 of the 20 spectra. Particularly, for 1ES 0502+675 and 1ES 1727+502, the resulting values of $\chi^2(df) = 38.2(14)$ and $\chi^2(df) = 32.7(14)$ are too large to be acceptable. The corresponding probability to obtain a larger value of $\chi^2$ is $p(\chi^2 > 38.2, df = 14) = 4.8 \times 10^{-4}$ and $p(\chi^2 > 25.9, df = 14) = 3.2 \times 10^{-3}$, indicating a poor fit in both cases. Upon inspecting the SEDs and the residuals in figures 33 and 42, additional features in the spectrum are present which are not well described by the model.

Following the same approach, we present the obtained TS values for all the sources in table 4, as well as their corresponding significance levels derived from null distribution for each source. As is evident from table 4, the other sources show a similar preference for hypotheses $H_1$ with photon-ALPs mixing.

In order to test the overall preference of the joint data sets, we combine the TS for the individual sources:

$$TS_{\text{tot}} = \sum_i TS_i,$$

where $TS_i$ is the test statistics for each individual source. Similarly, we combine the PE results from the individual sources in a bootstrapping approach. In order to do so, we take $10^7$ sequences of 20 uniform random deviates $n_1, \ldots, n_{20}$ in order to combine the sources in a random way:

$$PE = \{(TS_{n_1}, \ldots, TS_{n_{20}})|n_1, \ldots, n_{20} \in \{1, \ldots, 400\}\}.$$

This way, we calculate a distribution of $10^7$ values of $TS^{PE}$ derived from the PE:

$$TS^{PE} = \sum_i TS_{n_i}.$$
distribution. We estimate the distribution for small values of based hypotheses test, we find the NCD fit a poor description of the underlying simulated values of 4.5 Combined HE and VHE spectra

The large collection area of ground-based instruments extends the high energy (HE) range accessible with Fermi-LAT towards very high energies (VHE), where photon statistics limit

\[
\chi^2 \left( z \right) = \frac{1}{2} \ln \left( \frac{1}{2\pi n} \right) - \frac{1}{2} \sum_{i=1}^{n} \left( \frac{y_i - \mu_i}{\sigma_i} \right)^2
\]

in a similar way: we add up the individual \( \Delta \chi^2 \) values to obtain \( \Delta \chi^2_{\text{tot}} \), and generate \( 10^7 \) values of \( (\Delta \chi^2)^{PE}_{\text{tot}} \) similar to the procedure outlined in eqs. (4.9), (4.10).

The resulting distributions of \( TS^{PE} \) and \( (\Delta \chi^2)^{PE}_{\text{tot}} \) are shown in figure 4. The probability density function can be approximated by a NCD, similar to the distributions for the individual sources. The distribution of \( TS^{PE} \) is well fit by the NCD and the probability to find a value of \( TS^{PE} > TS_{\text{tot}} \) can be estimated from the best-fitting NCD\(^7\) to be \( p(TS^{PE} > TS_{\text{tot}} = 98.9; df = 140.20, nc = 162.49) = 1.22 \times 10^{-7} \), corresponding to a \( z \)-score of 5.3. For the \( \Delta \chi^2 \) based hypotheses test, we find the NCD fit a poor description of the underlying simulated distribution for small values of \( \Delta \chi^2 \). For larger values of \( \Delta \chi^2 \) the fit matches closely the distribution. We estimate the \( z \)-score to be smaller than the value found for the \( TS \)-based distribution at 1.4. This is consistent with the findings from the individual sources.

4.5 Combined HE and VHE spectra

The large collection area of ground-based instruments extends the high energy (HE) range accessible with Fermi-LAT towards very high energies (VHE), where photon statistics limit

\(^7\)A similar value is obtained by counting the number of entries in the simulated distribution with \( TS^{PE} > TS_{\text{tot}} \).
the sensitivity for space based instruments. The downside of the ground-based technique is a limited field of view. Therefore, the VHE spectrum is in most cases recorded during flaring states whereas the HE spectrum is recorded quasi-continuously with the all-sky instrument of Fermi-LAT. The flare-selected observation of AGN with ground based instruments introduces a bias in the observed energy spectrum towards a high flux-state which is not necessarily representative of a truly time-averaged spectrum.

In the following, we consider examples for the combination of HE and VHE data taken from PKS 2155-304 \((z = 0.116)\) and Mkn 421 \((z = 0.031)\), where HE and VHE data are recorded contemporaneously with Fermi-LAT and ground-based instruments.

### 4.5.1 Combined spectrum of PKS 2155-304

The nearby X-ray selected AGN PKS 2155-304 is the first extra-galactic very high energy gamma-ray source discovered in the southern sky [40]. It has been closely monitored, both during periods of quiescence as well as during flares [41].

We consider a quasi-simultaneous observation to avoid the combination of data sets averaged over different flux states. Non-simultaneous spectral data could lead to an apparent spectral break or irregularities close to the transition energy of the two measurements. The constraint on available contemporaneous observation time leads to larger statistical uncertainties on the detected photon numbers which in turn reduce the sensitivity for spectral features. During contemporaneous observations of PKS 2155-304 with H.E.S.S.-II and Fermi-LAT in 2013, a spectral break between the HE and VHE data is observed [42]. The H.E.S.S. Phase II observations achieved a reduced energy threshold in comparison with the previous measurements recorded with the smaller H.E.S.S. Phase I instruments [41]. The lower threshold of H.E.S.S. II observations improves the overlap in the energy range covered with space and ground based instruments. We re-analyse the contemporaneous Fermi-LAT data set used by [42] with identical energy bins to combine the two measurements.

We present in figure 5 the scan of \(\Delta \chi^2(B, s)\) from the combined energy spectrum for the ALP hypothesis \(H_1\). The global best-fitting parameters are found to be at \(\vec{B} = 5.5 \mu G\), with
Figure 5. $\Delta \chi^2$ for a grid of values of B-field strength $B$ and distance $s$. The color bar indicates the $\Delta \chi^2$ values when fitting the combined contemporaneous LAT and H.E.S.S. data in 2013. The black point marker indicates the local maximum of $\Delta \chi^2$ derived from the fit of the SED to the combined spectrum, while the white triangle marker represents the global best-fitting parameters.

$\hat{s} = 0.2$ kpc, where $\Delta \chi^2 = 4.1$ is obtained. As can be seen from figure 5, the local maximum $(\hat{B}_0, \hat{s}_0)$ (indicated with a black point) coincides with the global maximum (indicated with a white triangle).

The resulting spectral energy distribution is shown in figure 6. The spectral break is observed at an energy of $(48 \pm 12)$ GeV when fitting a broken-power law to the combined SED. The flux measurements in the overlapping energy range between 80 GeV and 300 GeV are consistent between the two instruments. The $H_0$ hypothesis is not providing a good description of the data while the $H_1$ hypothesis improves slightly the fit by $\Delta \chi^2 = 4.1$. Using mock data sets, we estimate the significance in a similar way as before. The resulting distribution for $\Delta \chi^2$ and a NCD fit function is shown in figure 6 (right panel). The $z$-score for the improvement is estimated to be $\approx 1.6$.

4.5.2 Combined spectrum from Mkn 421

The northern, nearby AGN Mkn 421 ($z = 0.031$) is a highly variable BL Lac type object that has been closely monitored since the discovery of its VHE emission [43]. While a number of simultaneous multi-wavelength observations have been carried out for this source, we select the result reported by [44] on a simultaneous observation campaign with Fermi-LAT and the MAGIC telescopes from January to June 2009. During this campaign, the combined energy spectrum from the two instruments covers a very broad energy range with substantial overlap between the two instruments.

The scan of the parameters $s$ and $B$ for the combined spectrum shows several maxima which would favor either a large magnetic field of several $\mu$G on kpc scales or a very weak magnetic field of several nG over Mpc distances (see figure 7). The chosen the local maximum, corresponding to a minimum energy, is marked with a black cross in figure 7 where the resulting critical energy $\approx 100$ MeV (see eq. (2.10)).
Figure 6. Left panel: the spectral energy distribution for PKS 2155-304 during contemporaneous observations with H.E.S.S.-II and Fermi-LAT in 2013. The red data points represent the 2013 LAT observations, and the black data points are from H.E.S.S during the same year. The blue solid and green dashed lines are the best-fitting models under $H_0$ and $H_1$ hypotheses respectively. The cyan solid and gray dashed lines stand for the photon surviving probabilities in different regions along the line of sight. Right panel: simulated null distribution from $\Delta \chi^2$ test for 2013 H.E.S.S and LAT observations. The black dashed line indicates a fit to the distribution with a non-central $\chi^2$ function. The red solid line represents the resulting cumulative distribution function (CDF). The $\Delta \chi^2$ value derived from the original data is marked as a blue (dot-dash) vertical line.

Figure 7. $\Delta \chi^2$ distribution as functions of B-field strength $B$ and distance $s$. The color bar indicates the $\Delta \chi^2$ values when fitting the combined time-averaged LAT and MAGIC data [44]. The black point marker indicates the local maximum of $\Delta \chi^2$ derived from the fit of the SED to the time averaged spectrum, while the white triangle marker stands for the global maximum of $\Delta \chi^2$. 
Figure 8. Left panel: the spectral energy distribution for Markarian 421 during contemporaneous observations with MAGIC and Fermi-LAT in 2009. The red data points represent the 2009 LAT observations, and the black data points are from MAGIC [44] during the same year. The blue solid and green dashed lines are the best-fitting models under $H_0$ and $H_1$ hypotheses respectively. The cyan solid and gray dashed lines stand for the photon surviving probabilities in different regions along the line of sight. Right panel: simulated null distribution from $\Delta \chi^2$ test for 2009 MAGIC and LAT observations. The black dashed line indicates a fit to the distribution with a non-central $\chi^2$ function. The red solid line represents the resulting cumulative distribution function (CDF). The $\Delta \chi^2$ value derived from the original data is marked as a blue (dot-dash) vertical line.

The SED for Mkn 421 is obtained by reanalysing Fermi-LAT data from the observation season covered with MAGIC from January to June 2009 [44]. The resulting SED is displayed in figure 8. The spectrum shows a softening just below TeV energies, deviating noticeably from the log-parabola shape (green dashed line in figure 8). The fit under the alternative $H_1$ hypothesis improves the goodness of fit by $\Delta \chi^2 = 12.6$ such that the resulting $\chi^2_{H_1} = 20.7$ for 13 degrees of freedom. This value is slightly larger than expected due to two flux points between 100 and 200 GeV which deviate by more than two standard deviations from the fit.

The z-score of the improvement is estimated to be 1.8 (see figure 8, right panel).

5 Discussion

The search for spectral modulations in extra-galactic energy spectra has been carried out for 20 objects that have been selected to provide an optimized coverage in energy. For 18 sources (see table 4), the fits show a consistent improvement when including a photon-ALPs conversion (hypothesis $H_1$) in comparison to the null hypothesis ($H_0$). When inspecting the individual spectra (see figures 28–45), the photon-ALPs conversion in the GMF and the magnetic field intrinsic to the source leads to a rich phenomenology of spectral shapes. The resulting breaks, dips, and bumps occur predominantly at the critical energy (see eq. (2.10)) specific to the GMF and the source-intrinsic magnetic field.

The most significant improvement can be seen as expected in the spectra which have the largest signal-to-noise ratio, i.e. Mkn 421 (figure 2) with $TS = 18.5$ and NGC1275 (figure 31) with $TS = 19.8$. Another source with a well-measured spectrum is PG 1553+113 (figure 40). The spectrum has apparently several features that are not predicted in our model. Subsequently, the resulting $TS = -4.2$ would favor the $H_0$ hypothesis. However, the source
could be embedded in a cluster environment where weak mixing in the turbulent magnetic field provides a better description of the observed spectrum.

The findings obtained with the likelihood-method have been largely confirmed when fitting the SED with a $\chi^2$-based approach. The wider binning leads to an under-sampling of the spectral features that are visible in the spectra obtained for the likelihood analysis. The resulting significance in the $\chi^2$-based approach is therefore smaller than for the likelihood approach. The $\chi^2$-based approach is however useful when combining data sets from Fermi-LAT with ground-based measurements. We have demonstrated that for contemporaneous data-sets on PKS2155-304 and Mkn 421, the energy range can be extended in a meaningful way. However, no additional features are observed in the wider energy range. In the case of PKS 2155-304, the re-conversion of ALPs leads to an enhanced flux at energies exceeding a few TeV which is slightly favored by the data.

The combination of the results obtained with the relevant likelihood-analysis has been carried out for all 20 sources. When combining the likelihood results for the local maxima in the $B$-$s$ plane, we find a total TS value of $TS_{\text{tot}} = 98.9$. The local maxima is chosen to minimize the energy requirement to sustain a magnetic field with energy density $\propto B^2$ over a volume $\propto s^3$. This is considerably smaller than the value found when combining the global maxima of all sources with $TS'_{\text{tot}} = 133.6$.

A bootstrap-type combination of the same analyses carried out on mock data-sets that have been simulated under the null hypothesis are used to estimate the significance. We estimate the chance probability to find a $TS_{\text{tot}}$ value larger than 98.9 to be $1.2 \times 10^{-7}$ corresponding to a significance of 5.3 $\sigma$. For the global maximum, the estimated significance reaches 6 $\sigma$.

The required values of average transversal magnetic field $\hat{B}_0$ and extension $\hat{s}_0$ found for the individual sources fall into a wide range covering several orders of magnitude as shown in figure 9.

We compare in the same figure the values found in the fitting procedure with the range of values for magnetic fields possibly present in the vicinity of the considered sources. This includes the magnetic field in the outer regions of the jet (lobes) [45–47] as well as the magnetic field present in the host galaxy. In the wider vicinity of the source, we can expect that some objects are located in galaxy groups or galaxy clusters which are known to support an intracluster magnetic field (ICMF) with a turbulent and large scale component [16, 33–35, 48–52]. Recently, low-frequency radio-observations have revealed the presence of a large-scale magnetic field in the circumgalactic medium (CGM) [53].

Finally, the IGMF in filaments [54–60] along the line of sight could contribute additional conversion regions. The IGMF [30] in voids, however, is not relevant.

We note that the estimated values for $\hat{B}$ and $\hat{s}$ found for the 20 sources are nicely aligned with the astrophysically known magnetic fields. There is a noticeable cluster of six sources with $B = 20 \mu G - 30 \mu G$ for a spatial scale between 150 pc–300 pc. Similar large-scale fields are present in the central 200 pc of the Milky Way (galactic center field, GCF) [61], suggesting that the photon-ALPs conversion takes place in a similar environment in these sources.

In addition, we also indicate the prediction for formation of magnetic fields from magnetohydrodynamical simulation [62, 63]. The result of the simulation traces well the observed values indicated in figure 9.

\footnote{The converted B-field values shown here are from Illustris TNG-300 simulation setup in ref. [62].}
The result obtained here have been found under the assumption of fixed values for mass $m_a = 3.6\,\text{neV}$ and coupling $g_{a\gamma\gamma} = 2.3 \times 10^{-10}\,\text{GeV}^{-1}$ [17], that are not consistent with the bounds provided by CAST [21] (see however ref. [64] for a consistent interpretation of the two results). It is important to note, that the features visible in the energy spectra can also be fit with values for the coupling consistent with the bound from CAST ($g_{a\gamma\gamma} < 6.6 \times 10^{-11}\,\text{GeV}^{-1}$, 95% c.l.). In this case, the product of required magnetic field and length scale would need to be increased by a factor of $\approx 4$, which would not lead to unreasonable values of these parameters. However, more recent constraints for $g_{a\gamma\gamma} < 5.4 \times 10^{-12}\,\text{GeV}^{-1}$ (95% c.l.) have been derived from a re-analysis of the polarization from magnetized white dwarfs [65]. In this case, the necessary increase of the product of $B$ and $s$ to be $\approx 40$ would push the best-fitting values to the upper end of astrophysically motivated values (see figure 9).

6 Summary

- The fits to high-energy spectra of 20 extra-galactic gamma-ray sources improves significantly with $5.3(6.0)\,\sigma$ when including photon-ALPs mixing in a homogeneous magnetic field $\hat{B}_0$ with spatial extension $\hat{s}_0$ left free to vary for a fixed $m_a$ and $g_{a\gamma\gamma}$. The values $\hat{s}_0$, $\hat{B}_0$ relate to the local maximum in the TS with the additional condition that the total energy in the magnetic field $\propto \hat{B}_0^2 \hat{s}_0^3$ is minimized. The value in the parentheses corresponds to the global maximum.
• The individual sources with strong indications for additional spectral features present in the Fermi-LAT data are NGC1275 with 3.6(3.6) σ and Mkn 421 with also 3.6(3.6) σ.

• The range of values found for $\hat{B}_0$ is consistent with expected and plausible values for the magnetic field strength found in astrophysical environments characterized by the length scales of $s_0$ from several 100 pc to several 100 kpc (see figure 9).

• The observations of spectral modulations in AGN establish the disappearance channel of photon-ALPs mixing which is complementary to the appearance channel (anomalous transparency) that has provided the first indications for photon-ALPs mixing in gamma-ray spectra.

• The result shown here is degenerate for choosing a particular combination of coupling $g_{a\gamma\gamma}$ and mass $m_a$ to achieve the required conversion probability $p_{\gamma\rightarrow a} \propto g_{a\gamma\gamma}^2 B^2 s^2$ above the critical energy $E_c \propto m_a^2 / (g_{a\gamma\gamma} B)$. In this regards, the result presented here remains valid for different choices of $g_{a\gamma\gamma}$ and $m_a$ which would be consistent with other exclusion limits and astrophysical expectations for magnetic field strength.

Acknowledgments

Part of this work has made use of data and software provided by the Fermi Science Support Center. Q.Y. acknowledges the support from China Scholarship Council and the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy — EXC 2121 “Quantum Universe” — 390833306.

A Additional fit-results

In table 5 we list the best-fitting parameters estimated using the $\chi^2$-minimization under the null-hypothesis (see table 2 for the corresponding likelihood-fit results). The fit-results obtained with the $\chi^2$-method under the alternative hypothesis and evaluated at the local minimum are listed in table 6 (see table 3 for the likelihood-fit results). In tables 7 and 8 we present the global best-fitting parameters with the $\chi^2$ and likelihood methods respectively (supplementary to the information presented in table 9). Finally, the table 9 summarizes the result of the hypotheses tests when considering the global extrema (compare with table 4 for the local extrema).

In the following figures (figures 10 to 27) we present the $(B, s)$ grid maps with likelihood and $\chi^2$ fitting for the sources in our sample collection. The corresponding best-fitting spectral energy distributions are provided in figures 28 to 45.
Table 5. Best-fitting parameters for the null hypothesis with the $\chi^2$ method using the modeled spectra from eq. (4.3). The estimated uncertainties (1$\sigma$) for each fitting parameters are listed as well. The value of $E_b=10^5$ MeV is fixed, the normalisation is given in units of $10^{-15}$ MeV$^{-1}$cm$^{-2}$s$^{-1}$.

| AGN name       | $N_0$        | $\alpha$   | $\beta \times 10^{-3}$ |
|----------------|--------------|-------------|------------------------|
| 1ES 0033+595   | 0.983(0.115) | 1.71(0.08)  | 1(13)                  |
| 3C 66A        | 1.10(0.09)   | 2.28(0.04)  | 45(5)                  |
| PKS 0301-243  | 0.509(0.064) | 2.17(0.06)  | 36(8)                  |
| NGC 1275      | 0.802(0.046) | 2.70(0.02)  | 70(3)                  |
| PKS 0447-439  | 1.29(0.10)   | 2.20(0.04)  | 55(5)                  |
| 1ES 0502+675  | 0.86(0.07)   | 2.50(0.03)  | –                      |
| 1ES 0806+524  | 0.46(0.05)   | 2.11(0.06)  | 33(8)                  |
| 1ES 1011+496  | 1.15(0.09)   | 2.06(0.04)  | 32(5)                  |
| Markarian 421 |              |             |                        |
| 10yrs LAT     | 6.34(0.20)   | 1.92(0.02)  | 22(2)                  |
| simul. LAT+MAGIC | 3.28(0.18) | 2.12(0.02)  | 50(5)                  |
| Markarian 180 | 0.226(0.026) | 2.19(0.03)  | –                      |
| 1ES 1215+303  | 0.772(0.069) | 2.28(0.04)  | 48(5)                  |
| 1ES 1218+304  | 1.02(0.07)   | 2.29(0.02)  | –                      |
| PKS 1440-389  | 0.484(0.06)  | 2.20(0.07)  | 63(11)                 |
| PG 1553+113   | 3.96(0.21)   | 1.87(0.03)  | 37(5)                  |
| Markarian 501 | 2.41(0.13)   | 1.86(0.03)  | 17(4)                  |
| 1ES 1727+502  | 0.344(0.033) | 2.20(0.02)  | –                      |
| 1ES 1959+650  | 1.60(0.11)   | 1.98(0.04)  | 26(5)                  |
| PKS 2005-489  | 0.572(0.043) | 2.18(0.02)  | –                      |
| PKS 2155-304  |              |             |                        |
| 10yrs LAT     | 2.44(0.13)   | 2.13(0.03)  | 40(3)                  |
| simul. LAT+H.E.S.S. | 1.32(0.04) | 2.22(0.03)  | 53(7)                  |
| 1ES 2344+514  | 0.321(0.06)  | 2.23(0.11)  | 61(16)                 |

Figure 10. 1ES 0033+595, same as figure 1.
| AGN name        | $N_0$       | $\alpha$   | $\beta \times 10^{-3}$ | $B_0$     [μG] | $\delta_0$ [kpc] |
|-----------------|-------------|-------------|------------------------|------------|-----------------|
| 1ES 0033+595    | 1.74(0.20)  | 1.78(0.08)  | 188(12)                | 7547.5(3281.5) | 1.5(0.6)       |
| 3C 66A          | 1.89(0.26)  | 2.20(0.05)  | 46(5)                  | 374.7(62.6)    | 6.9(0.8)       |
| PKS 0301-243    | 0.950(0.145)| 2.18(0.12)  | 46(13)                 | 21672.5(2918.8)| 0.3(0.01)      |
| NGC 1275        | 1.47(0.02)  | 2.74(0.01)  | 76(1)                  | 39621.7(317.6)| 0.1(1.6)       |
| PKS 0447-439    | 2.46(0.22)  | 2.30(0.07)  | 909                    | 1731.8(283.0)  | 2.0(0.2)       |
| 1ES 0502+675    | 1.35(0.21)  | 2.59(0.05)  | --                     | 104.4(54.0)    | 53.5(17.4)     |
| 1ES 0806+524    | 0.581(0.075)| 2.00(0.07)  | 21(9)                  | 25.5(10.2)     | 202.6(36.2)    |
| 1ES 1011+496    | 1.42(0.14)  | 1.98(0.05)  | 24(6)                  | 35.7(7.3)      | 170.5(17.0)    |
| Markarian 421   | 10 yrs LAT  | 8.71(0.43)  | 1.84(0.02)  | 16(3)      | 16.5(6.4)      | 242.0(35.1)      |
| simul. LAT+MAGIC| 7.25(0.37)  | 2.15(0.02)  | 71(5)                  | 4344.2(845.6)  | 1.0(0.1)       |
| Markarian 180   | 0.308(0.040)| 2.25(0.03)  | --                     | 20.2(11.0)     | 226.2(72.9)    |
| 1ES 1215+303    | 1.44(0.16)  | 2.36(0.07)  | 69(12)                 | 7385.9(5817.8)| 0.4(0.3)       |
| 1ES 1218+304    | 1.98(0.14)  | 2.29(0.02)  | --                     | 295842.8(65007.2)| 0.0(0.01)     |
| PKS 1440-389    | 0.859(0.121)| 2.38(0.08)  | 110(12)                | 2326.0(1403.4)| 1.9(0.5)       |
| PG 1553+113     | 7.40(0.40)  | 1.78(0.04)  | 40(5)                  | 840.1(88.9)    | 10.9(1.0)      |
| Markarian 501   | 4.07(0.38)  | 1.87(0.02)  | 24(3)                  | 29605.7(3114.0)| 0.2(0.02)      |
| 1ES 1727+502    | 0.479(0.044)| 2.23(0.02)  | --                     | 1355.6(341.8)  | 6.8(1.3)       |
| 1ES 1959+650    | 2.33(0.31)  | 1.89(0.05)  | 22(5)                  | 137.7(67.8)    | 11.1(3.4)      |
| PKS 2005-489    | 1.01(0.09)  | 2.24(0.02)  | --                     | 8025.7(2126.2)| 1.3(0.3)       |
| PKS 2155-304    | 10 yrs LAT  | 4.69(0.24)  | 2.16(0.03)  | 43(3)      | 60241.1(10007.3)| 0.1(0.01)      |
| simul. LAT+H.E.S.S.| 2.69(0.09)  | 2.34(0.02)  | 86(7)                  | 5589.7(1975.4)| 0.8(0.2)       |
| 1ES 2344+514    | 0.731(0.132)| 2.15(0.12)  | 75(17)                 | 619.9(204.6)  | 7.5(1.5)       |

Table 6. Best-fitting parameters of local maxima for ALP hypothesis with $\chi^2$ method. Parameters uncertainties (1σ) are included. The value of $E_\delta = 10^5$ MeV is fixed, the normalisation is given in units of $10^{-15}$ MeV$^{-1}$cm$^{-2}$s$^{-1}$.

Figure 11. 3C 66A, same as figure 1.
Table 7. Best-fitting parameters for ALP hypothesis with $\chi^2$ method using the modeled spectra from eq. (4.4). Parameters uncertainties ($1\sigma$) are included. The value of $E_0 = 10^5$ MeV is fixed, the normalisation is given in units of $10^{-15}$ MeV$^{-1}$cm$^{-2}$s$^{-1}$.

| AGN name       | $N_0$     | $\alpha$ | $\beta\times10^{-3}$ | $B$ [nG]   | $\delta$ [kpc] |
|----------------|-----------|-----------|-----------------------|------------|---------------|
| IES 0033+595   | 1.77(0.20)| 1.75(0.08)| 13(13)                | 17047.7(2689.8) | 3.8(0.6)      |
| 3C 66A        | 1.89(0.26)| 2.20(0.05)| 46(5)                 | 374.8(62.6) | 6.9(0.8)      |
| PKS 0301-243  | 0.955(0.078)| 2.17(0.05)| 46(5)                 | 88403.9(532.1) | 1.8(0.01)    |
| NGC 1275      | 1.43(0.13)| 2.75(0.03)| 78(4)                 | 33752.1(9973.8) | 0.1(0.03)   |
| PKS 0447-439  | 2.50(0.19)| 2.23(0.04)| 74(6)                 | 8922.0(54.8) | 57.7(0.4)    |
| IES 0502+675  | 1.42(0.17)| 2.57(0.03)| 19(10)                | 51.8(7.6)  | 278.5(28.4)  |
| IES 0806+524  | 0.617(0.085)| 1.98(0.07)| 19(10)                | 51.8(7.6)  | 278.5(28.4)  |
| IES 1011+496  | 1.79(0.16)| 1.89(0.04)| 16(6)                 | 120.9(1.6) | 855.7(8.9)   |
| Markarian 421 |           |           |                       |            |               |
| 10190 LAT      | 8.71(0.44)| 1.84(0.02)| 16(3)                 | 165.6(6.6) | 242.2(37.4)  |
| simul. LAT+H.E.S. | 7.25(0.37)| 2.15(0.02)| 71(5)                 | 4344.2(845.6) | 1.0(0.15)   |
| IES 1215+303  | 1.44(0.16)| 2.36(0.07)| 69(12)                | 7392.7(5743.8) | 0.4(0.3)    |
| IES 1218+304  | 2.00(0.14)| 2.30(0.02)| 30890.8(516.5) | 7.3(0.01)  |               |
| PKS 1440-389  | 0.931(0.119)| 2.28(0.08)| 91(12)                | 30894.1(26.7) | 200.5(0.2)  |
| PG 1553+113   | 7.29(0.16)| 1.88(0.01)| 53(1)                 | 2647.4(0.0) | 226832.3(0.4) |
| Markarian 501 | 4.40(0.25)| 1.85(0.03)| 15(5)                 | 59644.3(1303.1) | 2.5(0.1)   |
| IES 1727+502  | 0.446(0.042)| 2.18(0.02)| 30946.1(163.3) | 395.7(0.1) |
| IES 1959+650  | 2.75(0.29)| 1.81(0.05)| 13(7)                 | 180.6(1.8) | 627.7(3.5)   |
| PKS 2005-489  | 0.895(0.076)| 2.22(0.02)| 11432.8(151.3) | 20.4(0.3)  |
| PKS 2155-304  |           |           |                       |            |               |
| 10190 LAT      | 4.51(0.24)| 2.11(0.03)| 49(4)                 | 4912.4(1.4) | 925.6(0.2)   |
| simul. LAT+H.E.S. | 2.69(0.09)| 2.34(0.02)| 86(7)                 | 5589.7(1975.4) | 0.8(0.2)    |
| IES 2344+514  | 0.690(0.152)| 2.21(0.12)| 83(17)                | 1159.7(390.0) | 11.9(3.3)   |

Figure 12. PKS 0301-243, same as figure 1.

– 23 –
| AGN name        | $N_0$        | $\alpha$ | $\beta \times 10^{-3}$ | $E_0$ [MeV] | $B$ [nG] | $s$ [kpc] |
|-----------------|--------------|-----------|-------------------------|------------|---------|----------|
| 1ES 0033+595    | 0.629(0.025) | 1.54(0.03) | 42(12)                  | 3177       | 911.9(1.5) | 911.4(1.3) |
| 3C 66A          | 12.5(0.2)    | 1.80(0.01) | 43(6)                   | 1211       | 311.0(44.4) | 7.3(1.0)   |
| PKS 0301-243    | 11.1(0.4)    | 1.81(0.02) | 38(10)                  | 954.4      | 50660.9(314.0) | 1.3(0.01) |
| NGC 1275        | 102(2)       | 1.98(0.01) | 85(3)                   | 883.6      | 14007.6(694.6) | 0.2(0.01) |
| PKS 0447-439    | 7.09(0.13)   | 1.56(0.01) | 83(6)                   | 1605       | 2151.5(41.6) | 5.5(0.1)   |
| 1ES 0502+675    | 0.083(0.004) | 1.38(0.03) | –                       | 6322       | 830.6(0.7)  | 1000.0(0.7) |
| 1ES 0806+524    | 2.31(0.06)   | 1.79(0.02) | 12(10)                  | 1297       | 74.6(2.4)   | 435.4(12.4) |
| 1ES 1011+496    | 7.68(0.10)   | 1.73(0.01) | 17(5)                   | 1066       | 118.6(0.9)  | 723.0(5.0)  |
| Markarian 421   | 19.1(0.2)    | 1.69(0.005) | 13(2)                  | 1286       | 21.1(4.2)  | 216.3(18.4) |
| Markarian 180   | 0.182(0.008) | 1.70(0.03) | –                       | 2679       | 98.5(1.5)   | 870.1(11.9) |
| 1ES 1215+303    | 17.9(0.4)    | 1.81(0.01) | 53(7)                   | 1066       | 47661.7(202.6) | 1.4(0.01) |
| 1ES 1218+304    | 0.418(0.015) | 1.68(0.02) | –                       | 4442       | 241288.9(42.7) | 9.4(0.002) |
| PKS 1440-389    | 1.75(0.06)   | 1.51(0.03) | 100(13)                 | 2014       | 3331.2(38.9) | 11.7(0.1)  |
| PG 1553+113     | 5.66(0.09)   | 1.45(0.01) | 49(5)                   | 1847       | 3496.4(0.0)  | 98466.5(0.1) |
| Markarian 501   | 8.35(0.34)   | 1.70(0.01) | 17(5)                   | 1478       | 85669.0(71.4) | 3.2(0.003) |
| 1ES 1727+502    | 0.297(0.017) | 1.75(0.03) | –                       | 3005       | 226832.0(0.6) | 690.1(0.002) |
| 1ES 1959-650    | 3.39(0.06)   | 1.70(0.01) | 9(5)                    | 1733       | 89.5(0.9)   | 831.8(10.0) |
| PKS 2005-489    | 0.747(0.050) | 1.76(0.02) | –                       | 2398       | 21312.2(78.1) | 5.6(0.02)  |
| PKS 2155-304    | 30.9(0.4)    | 1.76(0.01) | 40(5)                   | 1136       | 344288.2(57.1) | 5.4(0.001) |
| 1ES 2344+514    | 1.07(0.05)   | 1.56(0.03) | 61(14)                  | 1938       | 482.4(82.1)  | 9.2(1.1)   |

Table 8. Best-fitting parameters for ALP hypothesis with likelihood method using the modeled spectra from eq. (4.4). The normalisation is given in units of $10^{-12}$ MeV$^{-1}$cm$^{-2}$s$^{-1}$. Parameters uncertainties (1σ) are included.

Figure 13. NGC 1275, same as figure 1.
Table 9. Best-fitting log-likelihood and $\chi^2$ values for null ($H_0$) and ALP hypotheses ($H_1$). TS values are calculated with eqs. (4.6) and (4.7) for likelihood ratio test and $\Delta \chi^2$ test respectively. Corresponding significance levels for both tests are listed as well.

| AGN name | $H_0$ ln($L_{\max}^0$) | $H_1$ ln($L_{\max}^1$) | TS | 2-score ($H_1/H_0$) | $H_0$ $\chi^2_{w/\text{ALP}}/df$ | $H_1$ $\chi^2_{w/\text{ALP}}/df$ | $\Delta \chi^2$ | 2-score ($H_1/H_0$) |
|----------|------------------------|------------------------|----|---------------------|--------------------------------|--------------------------------|----------------|---------------------|
| 1ES 0033+595 | 71253.4 | 71225.7 | 9.6 | 2.3 | 22.2/15 | 13.5/13 | 8.8 | 2.0 |
| 3C 66A | −122858.4 | −122856.5 | 3.8 | 2.0 | 20.6/15 | 16.3/13 | 4.3 | 2.3 |
| PKS 0301-243 | −154508.6 | −154507.9 | 1.4 | 0.6 | 16.3/15 | 16.3/13 | −0.1 | 0.5 |
| NGC 1275 | 26767.7 | 26777.6 | 19.8 | 3.6 | 25.6/15 | 22.4/13 | 3.2 | 1.8 |
| PKS 0447-439 | −146200.2 | −146199.1 | 2.3 | 2.0 | 26.2/15 | 22.6/13 | 3.6 | 2.1 |
| 1ES 0502+675 | −4650.7 | −4656.2 | 7.0 | 1.3 | 41.9/16 | 36.2/14 | 5.7 | 1.0 |
| 1ES 0806+524 | −150751.7 | −150750.3 | 2.9 | 0.2 | 20.5/15 | 16.4/13 | 4.1 | 0.5 |
| 1ES 1011+496 | −153505.0 | −153500.7 | 8.6 | 1.6 | 12.7/15 | 8.0/13 | 4.7 | 0.7 |
| Markarian 421 | 10yr LAT | −130615.4 | −130606.2 | 18.5 | 3.6 | 28.8/15 | 15.5/13 | 13.3 | 2.7 |
| simul. LAT+MAGIC | −132628.4 | −132627.7 | 1.4 | 0.01 | 23.8/16 | 19.8/14 | 4.0 | 0.5 |
| Markarian 180 | −143988.2 | −143984.0 | 8.4 | 2.2 | 15.5/15 | 15.4/13 | 2.1 | 1.2 |
| 1ES 1215+303 | −145577.3 | −145576.5 | 1.6 | 1.3 | 19.0/16 | 19.9/14 | −0.9 | 1.1 |
| 1ES 1218+304 | 60781.3 | 60783.8 | 5.0 | 1.5 | 18.9/15 | 16.1/13 | 2.7 | 0.8 |
| PKS 1440-389 | −152448.5 | −152447.6 | 1.7 | 0.4 | 17.8/15 | 14.7/13 | 3.1 | 0.5 |
| PG 1553+113 | −95747.1 | −95742.8 | 8.7 | 1.7 | 18.5/15 | 12.8/13 | 5.7 | 1.0 |
| Markarian 501 | −154208.5 | −154205.2 | 6.8 | 1.4 | 26.7/16 | 22.7/14 | 3.9 | 0.3 |
| 1ES 1727+502 | −49456.2 | −49453.1 | 6.3 | 1.1 | 21.6/15 | 13.5/13 | 8.1 | 1.5 |
| 1ES 1959+650 | −166314.9 | −166307.9 | 13.6 | 2.5 | 33.9/16 | 17.2/14 | 16.7 | 2.7 |
| PKS 2005-489 | −145033.6 | −145020.7 | 1.7 | 1.5 | 15.8/15 | 14.3/13 | 1.5 | 1.1 |
| 1ES 2155-304 | −61482.2 | −61480.1 | 4.3 | 1.2 | 15.2/15 | 13.6/13 | 1.6 | 0.6 |

Figure 14. PKS 0447-439, same as figure 1.
Figure 15. 1E 0502+675, same as figure 1.

Figure 16. 1ES 0806+524, same as figure 1.

Figure 17. 1ES 1011+496, same as figure 1.
Figure 18. Markarian 180, same as figure 1.

Figure 19. 1ES 1215+303, same as figure 1.

Figure 20. 1ES 1218+304, same as figure 1.
Figure 21. PKS 1440-389, same as figure 1.

Figure 22. PG 1553+113, same as figure 1.

Figure 23. Markarian 501, same as figure 1.
Figure 24. 1ES 1727+502, same as figure 1.

Figure 25. 1ES 1959+650, same as figure 1.

Figure 26. PKS 2005-304, same as figure 1.
Figure 27. 1ES 2344+514, same as figure 1.

Figure 28. 1ES 0033+595, same as figure 2.

Figure 29. 3C 66A, same as figure 2.
Figure 30. PKS 0301-243, same as figure 2.

Figure 31. NGC 1275, same as figure 2.

Figure 32. PKS 0447-439, same as figure 2.
Figure 33. 1ES 0502+675, same as figure 2.

Figure 34. 1ES 0806+524, same as figure 2.

Figure 35. 1ES 1011+496, same as figure 2.
Figure 36. Markarian 180, same as figure 2.

Figure 37. 1ES 1215+303, same as figure 2.

Figure 38. 1ES 1218+304, same as figure 2.
Figure 39. PKS 1440-389, same as figure 2.

Figure 40. PG 1553+113, same as figure 2.

Figure 41. Markarian 501, same as figure 2.
Figure 42. 1ES 1727+502, same as figure 2.

Figure 43. 1ES 1959+650, same as figure 2.

Figure 44. PKS 2005-489, same as figure 2.
Figure 45. 1ES 2344+514, same as figure 2.

References

[1] R.D. Peccei and H.R. Quinn, Constraints Imposed by CP Conservation in the Presence of Instantons, Phys. Rev. D 16 (1977) 1791 [arXiv:hep-ph/9502204].

[2] R.D. Peccei and H.R. Quinn, CP Conservation in the Presence of Instantons, Phys. Rev. Lett. 38 (1977) 1440 [arXiv:hep-ph/9502204].

[3] P. Svrcek and E. Witten, Axions In String Theory, JHEP 06 (2006) 051 [hep-th/0605206].

[4] J.P. Conlon, The QCD axion and moduli stabilisation, JHEP 05 (2006) 078 [hep-th/0602233].

[5] M. Cicoli, M. Goodsell and A. Ringwald, The type IIB string axiverse and its low-energy phenomenology, JHEP 10 (2012) 146 [arXiv:1206.0819].

[6] J. Preskill, M.B. Wise and F. Wilczek, Cosmology of the Invisible Axion, Phys. Lett. B 120 (1983) 127.

[7] L.F. Abbott and P. Sikivie, A Cosmological Bound on the Invisible Axion, Phys. Lett. B 120 (1983) 133.

[8] M. Dine and W. Fischler, The Not So Harmless Axion, Phys. Lett. B 120 (1983) 137.

[9] J. Jaeckel, A Family of WISPy Dark Matter Candidates, Phys. Lett. B 732 (2014) 1 [arXiv:1311.0880].

[10] A. De Angelis, O. Mansutti and M. Roncadelli, Axion-Like Particles, Cosmic Magnetic Fields and Gamma-Ray Astrophysics, Phys. Lett. B 659 (2008) 847 [arXiv:0707.2695].

[11] D. Hooper and P.D. Serpico, Detecting Axion-Like Particles With Gamma Ray Telescopes, Phys. Rev. Lett. 99 (2007) 231102 [arXiv:0706.3203].

[12] M. Simet, D. Hooper and P.D. Serpico, The Milky Way as a Kiloparsec-Scale Axionscope, Phys. Rev. D 77 (2008) 063001 [arXiv:0712.2825].

[13] A. De Angelis, G. Galanti and M. Roncadelli, Relevance of axion-like particles for very-high-energy astrophysics, Phys. Rev. D 84 (2011) 105030 [arXiv:1106.1132].

[14] D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. Montanino and M. Roncadelli, Hardening of TeV gamma spectrum of AGNs in galaxy clusters by conversions of photons into axion-like particles, Phys. Rev. D 86 (2012) 075024 [arXiv:1207.0776].
[15] G.I. Rubtsov and S.V. Troitsky, Breaks in gamma-ray spectra of distant blazars and transparency of the Universe, *JETP Lett.* **100** (2014) 355 [arXiv:1406.0239] [SPIRE].

[16] M. Libanov and S. Troitsky, On the impact of magnetic-field models in galaxy clusters on constraints on axion-like particles from the lack of irregularities in high-energy spectra of astrophysical sources, *Phys. Lett. B* **802** (2020) 135252 [arXiv:1908.03084] [SPIRE].

[17] J. Majumdar, F. Calore and D. Horns, Search for gamma-ray spectral modulations in Galactic pulsars, *JCAP* **04** (2018) 048 [arXiv:1801.08813] [SPIRE].

[18] M. Meyer, D. Horns and M. Raue, First lower limits on the photon-axion-like particle coupling from very high energy gamma-ray observations, *Phys. Rev. D* **87** (2013) 035027 [arXiv:1302.1208] [SPIRE].

[19] K. Kohri and H. Kodama, Axion-Like Particles and Recent Observations of the Cosmic Infrared Background Radiation, *Phys. Rev. D* **96** (2017) 051701 [arXiv:1704.05189] [SPIRE].

[20] R. Bähre et al., Any light particle search II — Technical Design Report, 2013 *JINST* **8** T09001 [arXiv:1302.5647] [SPIRE].

[21] CAST collaboration, New CAST Limit on the Axion-Photon Interaction, *Nature Phys.* **13** (2017) 584 [arXiv:1705.02290] [SPIRE].

[22] G.A. Pallathadka et al., Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds, *JCAP* **11** (2021) 036 [arXiv:2008.08100] [SPIRE].

[23] G. Raffelt and L. Stodolsky, Mixing of the Photon with Low Mass Particles, *Phys. Rev. D* **37** (1988) 1237 [astro-ph/0607415] [SPIRE].

[24] A. Mirizzi, G.G. Raffelt and P.D. Serpico, Photon-axion conversion as a mechanism for supernova dimming: Limits from CMB spectral distortion, *Phys. Rev. D* **72** (2005) 023501 [astro-ph/0506078] [SPIRE].

[25] A. Mirizzi, G.G. Raffelt and P.D. Serpico, Photon-axion conversion in intergalactic magnetic fields and cosmological consequences, *Lect. Notes Phys.* **741** (2008) 115 [astro-ph/0607415] [SPIRE].

[26] G. Galanti, F. Tavecchio, M. Roncadelli and C. Evoli, Blazar VHE spectral alterations induced by photon–ALP oscillations, *Mon. Not. Roy. Astron. Soc.* **487** (2019) 123 [arXiv:1811.03548] [SPIRE].

[27] A. Dobrynina, A. Kartavtsev and G. Raffelt, Photon-photon dispersion of TeV gamma rays and its role for photon-ALP conversion, *Phys. Rev. D* **91** (2015) 083003 [arXiv:1412.4777] [Erratum ibid. **95** (2017) 109905] [SPIRE].

[28] C. Csaki, N. Kaloper, M. Peloso and J. Terning, Super GZK photons from photon axion mixing, *JCAP* **05** (2003) 005 [hep-ph/0302030] [SPIRE].

[29] M.S. Pshirkov, P.G. Tinyakov and F.R. Urban, New limits on extragalactic magnetic fields from rotation measures, *Phys. Rev. Lett.* **116** (2016) 191302 [arXiv:1504.06546] [SPIRE].

[30] R. Durrer and A. Neronov, Cosmological Magnetic Fields: Their Generation, Evolution and Observation, *Astron. Astrophys. Rev.* **21** (2013) 62 [arXiv:1303.7121] [SPIRE].

[31] R. Jansson and G.R. Farrar, A New Model of the Galactic Magnetic Field, *Astrophys. J.* **757** (2012) 14 [arXiv:1204.3662] [SPIRE].

[32] FERMILAT collaboration, The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope, *Astrophys. J.* **892** (2020) 105 [arXiv:1905.10771] [SPIRE].

[33] J.S. Sanders, A.C. Fabian and R.J.H. Dunn, Non-thermal x-rays, a high abundance ridge and fossil bubbles in the core of the Perseus cluster of galaxies, *Mon. Not. Roy. Astron. Soc.* **360** (2005) 133 [astro-ph/0503318] [SPIRE].
[34] G.B. Taylor, N.E. Gugliucci, A.C. Fabian, J.S. Sanders, G. Gentile and S.W. Allen, *Magnetic fields in the center of the perseus cluster*, Mon. Not. Roy. Astron. Soc. 368 (2006) 1500 [astro-ph/0602622] [inSPIRE].

[35] FERMILAT collaboration, *Search for Spectral Irregularities due to Photon–Axionlike-Particle Oscillations with the Fermi Large Area Telescope*, Phys. Rev. Lett. 116 (2016) 161101 [arXiv:1603.06978] [inSPIRE].

[36] FERMILAT collaboration, *Fermipy: An open-source Python package for analysis of Fermi-LAT Data*, PoS ICRC2017 (2018) 824 [arXiv:1707.09551] [inSPIRE].

[37] FERMILAT collaboration, *Fermi Large Area Telescope Fourth Source Catalog*, Astrophys. J. Suppl. 247 (2020) 33 [arXiv:1902.10045] [inSPIRE].

[38] A. Dominguez et al., *Extragalactic Background Light Inferred from AEGIS Galaxy SED-type Fractions*, Mon. Not. Roy. Astron. Soc. 410 (2011) 2556 [arXiv:1007.1459] [inSPIRE].

[39] S.S. Wilks, *The Large-Sample Distribution of the Likelihood Ratio for Testing Composite Hypotheses*, Annals Math. Statist. 9 (1938) 60 [inSPIRE].

[40] P.M. Chadwick et al., *Pks 2155-304 — a source of the gamma-rays*, Astropart. Phys. 11 (1999) 145 [astro-ph/9812122] [inSPIRE].

[41] H.E.S.S. collaboration, *VHE gamma-ray emission of PKS 2155-304: spectral and temporal variability*, Astron. Astrophys. 520 (2010) A83 [arXiv:1005.3702] [inSPIRE].

[42] H.E.S.S. and LAT collaborations, *Gamma-ray blazar spectra with H.E.S.S. II mono analysis: The case of PKS 2155–304 and PG 1553+113*, Astron. Astrophys. 600 (2017) A89 [arXiv:1612.01843] [inSPIRE].

[43] M. Punch et al., *Detection of TeV photons from the active galaxy Markarian 421*, Nature 358 (1992) 477 [inSPIRE].

[44] LAT and MAGIC collaborations, *Fermi large area telescope observations of Markarian 421: The missing piece of its spectral energy distribution*, Astrophys. J. 736 (2011) 131 [arXiv:1106.1348] [inSPIRE].

[45] M. Meyer and J. Conrad, *Sensitivity of the Cherenkov Telescope Array to the detection of axion-like particles at high gamma-ray opacities*, JCAP 12 (2014) 016 [arXiv:1410.1556] [inSPIRE].

[46] F. Tavecchio, M. Roncadelli and G. Galanti, *Photons to axion-like particles conversion in Active Galactic Nuclei*, Phys. Lett. B 744 (2015) 375 [arXiv:1406.2303] [inSPIRE].

[47] I. Feain et al., *Faraday Rotation Structure on Kiloparsec Scales in the Giant Radio Lobes of Centaurus A*, Astrophys. J. 707 (2009) 114 [arXiv:0910.3458] [inSPIRE].

[48] K.T. Kim, P.P. Kronberg, P.E. Dewdney and T.L. Landecker, *The Halo and Magnetic Field of the Coma Cluster of Galaxies*, Astrophys. J. 355 (1990) 29.

[49] C.L. Carilli and G.B. Taylor, *Cluster magnetic fields*, Ann. Rev. Astron. Astrophys. 40 (2002) 319 [astro-ph/0110658] [inSPIRE].

[50] F. Govoni and L. Feretti, *Magnetic field in clusters of galaxies*, Int. J. Mod. Phys. D 13 (2004) 1549 [astro-ph/0410182] [inSPIRE].

[51] K. Subramanian, A. Shukurov and N.E.L. Haugen, *Evolving turbulence and magnetic fields in galaxy clusters*, Mon. Not. Roy. Astron. Soc. 366 (2006) 1437 [astro-ph/0505144] [inSPIRE].

[52] T. Akahori and D. Ryu, *Faraday Rotation Measure due to the Intergalactic Magnetic Field*, Astrophys. J. 723 (2010) 476 [arXiv:1009.0570] [inSPIRE].

[53] V. Heessen et al., *Detection of magnetic fields in the circumgalactic medium of nearby galaxies using Faraday rotation*, Astron. Astrophys. 670 (2023) L23 [arXiv:2302.06617].
[54] T. Vernstrom, B.M. Gaensler, S. Brown, E. Lenc and R.P. Norris, *Low Frequency Radio Constraints on the Synchrotron Cosmic Web*, *Mon. Not. Roy. Astron. Soc.* **467** (2017) 4914 [arXiv:1702.05069] [inSPIRE].

[55] S. Brown et al., *Limiting Magnetic Fields in the Cosmic Web with Diffuse Radio Emission*, *Mon. Not. Roy. Astron. Soc.* **468** (2017) 4246 [arXiv:1703.07829] [inSPIRE].

[56] V. Vacca et al., *Observations of a nearby filament of galaxy clusters with the Sardinia Radio Telescope*, *Mon. Not. Roy. Astron. Soc.* **479** (2018) 776 [arXiv:1804.09199] [inSPIRE].

[57] S.P. O’Sullivan et al., *The intergalactic magnetic field probed by a giant radio galaxy*, *Astron. Astrophys.* **622** (2019) A16 [arXiv:1811.07934] [inSPIRE].

[58] N. Locatelli et al., *New constraints on the magnetic field in cosmic web filaments*, *Astron. Astrophys.* **652** (2021) A80 [arXiv:2101.06051] [inSPIRE].

[59] T. Vernstrom et al., *Discovery of magnetic fields along stacked cosmic filaments as revealed by radio and X-ray emission*, *Mon. Not. Roy. Astron. Soc.* **505** (2021) 4178 [arXiv:2101.09331] [inSPIRE].

[60] E. Carretti et al., *Magnetic field strength in cosmic web filaments*, *Mon. Not. Roy. Astron. Soc.* **512** (2022) 945 [arXiv:2202.04607] [inSPIRE].

[61] F. Yusef-Zadeh et al., *Interacting Cosmic Rays with Molecular Clouds: A Bremsstrahlung Origin of Diffuse High Energy Emission from the Inner 2deg by 1deg of the Galactic Center*, *Astrophys. J.* **762** (2013) 33 [arXiv:1206.6882] [inSPIRE].

[62] F. Marinacci et al., *First results from the IllustrisTNG simulations: radio haloes and magnetic fields*, *Mon. Not. Roy. Astron. Soc.* **480** (2018) 5113 [arXiv:1707.03396] [inSPIRE].

[63] V. Springel et al., *First results from the IllustrisTNG simulations: matter and galaxy clustering*, *Mon. Not. Roy. Astron. Soc.* **475** (2018) 676 [arXiv:1707.03397] [inSPIRE].

[64] G.A. Pallathadka et al., *Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds*, *JCAP* **11** (2021) 036 [arXiv:2008.08100] [inSPIRE].

[65] C. Dessert, D. Dunsky and B.R. Safdi, *Upper limit on the axion-photon coupling from magnetic white dwarf polarization*, *Phys. Rev. D* **105** (2022) 103034 [arXiv:2203.04319] [inSPIRE].