Fundamental physics with blazar spectra: a critical appraisal

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ABSTRACT

Very-high-energy (VHE) BL Lac spectra extending above 10 TeV provide a unique opportunity for testing physics beyond the standard model of elementary particle and alternative blazar emission models. We consider the hadron beam, the photon to axion-like particle (ALP) conversion, and the Lorentz invariance violation (LIV) scenarios by analyzing their consequences and induced modifications to BL Lac spectra. In particular, we consider how different processes can provide similar spectral features (e.g. hard tails) and we discuss the ways they can be disentangled. We use HEGRA data of a high state of Markarian 501 and the HESS spectrum of the extreme BL Lac (EHBL) 1ES 0229+200. In addition, we consider two hypothetical EHBLs similar to 1ES 0229+200 located at redshifts \( z = 0.3 \) and \( z = 0.5 \). We observe that both the hadron beam and the photon-ALP oscillations predict a hard tail extending to energies larger than those possible in the standard scenario. Photon-ALP interaction predicts a peak in the spectra of distant BL Lacs at about \( 20 \text{–} 30 \text{ TeV} \), while LIV produces a strong peak in all BL Lac spectra around \( \sim 100 \text{ TeV} \). The peculiar feature of the photon-ALP conversion model is the production of oscillations in the spectral energy distribution, so that its detection/absence can be exploited to distinguish among the considered models. The above mentioned features coming from the three models may be detected by the upcoming Cherenkov Telescope Array (CTA). Thus, future observations of BL Lac spectra could eventually shed light about new physics and alternative blazar emission models, driving fundamental research towards a specific direction.

Key words: astroparticle physics – radiation mechanisms: non-thermal – BL Lacertae objects: general – galaxies: jets – gamma-rays: galaxies.

1 INTRODUCTION

Radio-loud active galactic nuclei (AGNs) are extragalactic accreting supermassive black holes (SMBHs) characterized by the formation of two collimated relativistic jets that develop in opposite directions. It is commonly accepted that the basic structure of observed AGNs is similar: the different associated phenomenology is mostly due to the different angle of view with which each source is observed at the Earth (Urry & Padovani 1995). When merely by chance one of the AGN jets is almost pointing toward the Earth, radio-loud AGNs are called blazars. Their emission spans the entire electromagnetic spectrum, from radio waves up to the very-high-energy (VHE) gamma-ray band. Blazar spectra are characterized by two broad bumps, the first one peaking in the IR-UV band, whose origin is the synchrotron emission from relativistic electrons in the jet, while the second one reaches its maximum at gamma-ray energies. The origin of this high-energy bump is still debated. Leptonic models (e.g. Maraschi, Ghisellini & Celotti 1992; Sikora, Begelman & Rees 1994; Bloom & Marscher 1996) attribute it to inverse Compton scattering of synchrotron radiation or external photons from the disc and/or clouds with the synchrotron emitting relativistic electrons. Hadronic models explain the photon high-energy emission as due to proton synchrotron emission or due to photons production (see e.g. Mannheim 1993a,b; Mücke et al. 2003).

Blazars are divided into two classes: flat spectrum radio quasars (FSRQs) and BL Lac objects (BL Lacs). FSRQs are powerful sources believed to be fed by an efficient accretion disc; moreover, they show optical emission lines produced by clouds of gas orbiting around the central SMBH and photoionized by UV photons from the disc. BL Lacs are less powerful and they do not display significant emission lines. These sources are believed to host a radiatively inefficient accretion flow unable to strongly ionize the gas surrounding the SMBH (e.g. Ghisellini, Maraschi & Tavecchio 2009; Righi, Tavecchio & Inoue 2019). Moreover, as de-

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scribed by the so-called blazar sequence (Fossati et al. 1998; Ghisellini, Righi, Costamante & Tavecchio 2017), BL Lac intrinsic gamma-ray spectra are generally harder than the FSRQs. In addition, in the latter case VHE photons are absorbed via the $\gamma\gamma$ FSR process when interacting with soft background photons emitted by the broad-line region (BLR) and the dusty torus.

Deviations from the standard spectra predicted by leptonic and/or hadronic models, induced by conventional or new physics effects, are expected at VHE. In this fashion, the best obvious candidates are represented by BL Lacs: this is the reason why we concentrate on this blazar subclass in the following. The detection of photons coming from close BL Lacs ($z < 0.1$) with energies above $20 - 30$ TeV and/or of photons from far BL Lacs ($z > 0.3$) with energies well above 1 TeV would be strong evidence that the current emission and/or propagation models of photons produced by BL Lacs are at least incomplete. The biggest challenge posed by extremely high energies and/or large distances is that high-energy photons suffer severe absorption interacting with the optical-UV radiation of the extragalactic background light (EBL, see e.g. De Angelis, Galanti & Roncalli 2013; Dwek & Krennrich 2013; Galanti, Tavecchio, Piccinini & Roncalli 2019). Several scenarios are envisioned to interpret such a possible detection. Starting from conventional physics, in hadronic models and in the absence of strong extragalactic magnetic fields, protons may travel and produce an electromagnetic cascade which may result in a hardening of the observed spectra that can be detected at energies up to $20 - 30$ TeV (e.g. Essey & Kusenko 2010; Essey, Kalashev, Kusenko & Beacom 2011; Murase, Dermer, Takami & Migliori 2012). Another possibility is that physics beyond the Standard Model (SM) of elementary particle physics, with the introduction of axion-like particles (ALPs), may extend the detectable BL Lac spectra at similar energies (Galanti, Tavecchio, Roncalli & Evoli 2019) thanks to photon-ALP oscillations which increase the effective Universe transparency (Galanti & Roncalli 2018b). Alternatively, Lorentz invariance violation (LIV) would modify the photon dispersion relation and, as a consequence, would produce an enhancement of the photon flux for energies above $20$ TeV (Kifune 1999; Protheroe & Meyer 2000). In the following, we will cursorily sketch the main properties of the three scenarios for BL Lac spectra by analyzing three sources: Markarian 501, 1ES 0229+200 and two hypothetical BL Lacs similar to the latter but placed at redshifts $z = 0.3$ and $z = 0.5$. In particular, we study the effects of the three considered scenarios on the observed BL Lac spectra, discussing their phenomenological analogies and differences. A quite important point, overlooked in current discussions, is that the hadron beam and the photon-ALP oscillations produce a quite similar observational feature, i.e. a photon excess in observed BL Lac spectra at high energies. A similar degeneracy exists for LIV spectra, predicting a strong peak around ~100 TeV, and photon-ALP oscillations in far-away sources. We will remark that the detection/absence of a spectral oscillatory behavior would discriminate among all scenarios, since that feature is peculiar to the photon-ALP model. In addition, we show that, should the photon-ALP induced spectral oscillatory behavior be detected, the photon-ALP predictions may give also an indication about the blazar emission mechanism.

Although BL Lacs are the best candidates for testing modified models and new physics, even recent observations of FSRQs up to energies above 20 GeV challenge current AGN models. In order to explain photon detection from FSRQs up to ~300 GeV, standard AGN models must be modified by placing the emission region far from the center (see e.g. Costamante et al. 2018b) or it is possible to maintain classical AGN models by invoking photon-ALP conversion (Tavecchio, Roncalli, Galanti & Bonnoli 2012).

Our analysis of new-physics-induced BL Lac spectral modification in the VHE band is of great importance for the oncoming Cherenkov Telescope Array (CTA)\(^1\) since it will be able to detect and precisely measure photons with energies up to above 100 TeV and it may shed light on deviations from standard models of photon emission and/or propagation and/or even give proof of physics beyond the SM. Although CTA represents the most promising observatory for such studies, also current Imaging Atmospheric Cherenkov Telescopes (IACTs) H.E.S.S. (High Energy Stereoscopic System)\(^2\), MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes)\(^3\) and VERITAS (Very Energetic Radiation Imaging Telescope Array System)\(^4\) and other gamma-ray facilities like HAWC (High-Altitude Water Cherenkov Observatory)\(^5\), GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus)\(^6\), LHAASO (Large High Altitude Air Shower Observatory)\(^7\), TAIGA-HiSCORE (Hundred Square km Cosmic Origin Explorer)\(^8\) and HERD (High Energy Cosmic Radiation Detection, Huang et al. 2016) may make a detection.

The paper is organized as follows. In Sect. 2 we describe the hadron beam model, in Sect. 3 we sketch the main properties and consequences of the photon-ALP interaction, in Sect. 4 we illustrate LIV and its effects, while we critically compare the byproducts of the three scenarios for BL Lac spectra in Sect. 5 and we draw our conclusions in Sect. 6.

## 2 HADRON BEAM SCENARIO

Standard hadronic models explain the second bump at gamma-ray energies as due to synchrotron emission by protons in the jet and/or photomeson production which produces gamma-ray photons due to neutral pion decay. A variant of the hadron model envisages that hadrons accelerated in the jet can escape in the form of a collimated beam of ultra-relativistic hadrons which, interacting with low-energy backgrounds, triggers electromagnetic cascades in extragalactic space (e.g. Essey & Kusenko 2010; Essey, Kalashev, Kusenko & Beacom 2011; Murase, Dermer, Takami & Migliori 2012).

Cosmic-ray-induced cascades may result in a hardening

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1. https://www.cta-observatory.org/
2. https://www.mpi-hd.mpg.de/lhm/HESS
3. https://magic.mpp.mpg.de/
4. http://veritas.sao.arizona.edu/
5. http://www.hawc-observatory.org/
6. gamma400.leddev.ru/gamma400.html
7. http://english.ifhep.cas.cn/ic/l/PHAASO/
8. www.desy.de/groups/astroparticle/score/en/
of the observed photon spectrum since the secondary photons produced suffer only a small path absorption due to the interaction with EBL photons. However, some important caveats must be taken into account. Primary cosmic rays are deflected by intense and structured magnetic fields. This is obviously the case for cluster and filament magnetic fields for cosmic rays with energies $E \lesssim 10^{10} \text{eV}$ (Murase, Dermer, Takami & Migliori 2012). Furthermore, the produced cascade may be deflected by the extragalactic magnetic field $B_{\text{ext}}$ so knowledge of its strength and structure is important. For $B_{\text{ext}} \gtrsim 10^{-15} \text{G}$ – which is however not so far from its lower limit (Neronov & Vovk 2010; Durrer & Neronov 2013; Pshirkov, Tinyakov & Urban 2016; Ackermann et al. 2018) – and a coherence length $L_{\text{coh}} = \mathcal{O}(1 \text{Mpc})$ the cosmic ray-induced cascade is so deflected that the hadron beam scenario would be unable to efficiently produce a surplus of photons at TeV energies (Tavecchio et al. 2010). As a high value of $B_{\text{ext}}$ isotropizes the cosmic ray distribution, it would increase the cosmic ray luminosity budget needed for a sizable production of secondary photons. In addition, the cascade radiation appears as hardly compatible with rapidly varying sources since the cascade process produces a time spread (Murase, Dermer, Takami & Migliori 2012). As a consequence, this model can be applied to 1ES 0229+200 and to similar extreme BL Lacs (e.g. Tavecchio, Romano, Landoni & Vercellone 2019) but not to the highly variable Markarian 501.

Taking into account the above-mentioned remarks, the hadron beam scenario predicts a hardening of the observed spectra that can be detected at energies up to 20–30 TeV (Tavecchio, Romano, Landoni & Vercellone 2019). The effect is more and more evident for more and more distant sources: in particular, for closer sources ($z \lesssim 0.3$) we expect a hard tail above $\sim 10$ TeV, while for sources at larger redshifts the tail is predicted at lower energies because of the high attenuation (e.g. Murase, Dermer, Takami & Migliori 2012).

3 AXION-LIKE PARTICLES

Axion-like particles (ALPs) are spin-zero, neutral, and very light pseudo-scalar bosons which are predicted by many extensions of the SM of particle physics such as String Theory (e.g. Jaeckel & Ringwald 2010; Ringwald 2012). ALPs are a generalization of the axion (for a review see Kim 1987; Cheng 1988; Kim & Carosi 2010) – the pseudo-Goldstone boson arising from the breakdown of the global Peccei-Quinn symmetry $U(1)_\text{PQ}$ which was proposed as a natural solution to the strong CP problem. ALPs differ from the original axion in two aspects. First, ALPs are supposed to interact primarily only with two photons: as a consequence, the additional Lagrangian $\mathcal{L}_{\text{ALP}}$ describing the ALP field $a$ and ALP interactions with the SM reads

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 + g_{\gamma\gamma} a E \cdot B, \quad (1)$$

where $E$ and $B$ denote the electric and magnetic components of the electromagnetic tensor $F_{\mu\nu}$, while $m_a$ and $g_{\gamma\gamma}$ are the ALP mass and the two-photon coupling of $a$, respectively. Furthermore, unlike the original axion, for ALPs $m_a$ and $g_{\gamma\gamma}$ exist in the literature (for a thorough discussion see Galanti & Roncadelli 2018b) but reasonable values appear to be $m_a = \mathcal{O}(10^{-10} \text{eV})$ and $g_{\gamma\gamma} = \mathcal{O}(10^{-11} \text{GeV}^{-1})$. In the presence of an external magnetic field, denoted by $B$, photon-ALP oscillations may occur (in Eq. (1) $E$ represents the propagating photon field) since the propagation eigenstates differ from the interaction eigenstates being the mass matrix of the $\gamma-a$ system off-diagonal. Only the component $B_T$ of $B$ which is transverse to the photon momentum $k$ couples to $a$ since $B_T$ belongs to the plane containing $E$ (see e.g. De Angelis, Galanti & Roncadelli 2011; Galanti & Roncadelli 2018a,b). Therefore, every magnetized environment represents a candidate for photon-ALP oscillations. An improved and physically meaningful at all energies modeling of photon-ALP oscillations inside domain-like magnetic fields is discussed in Galanti & Roncadelli (2018a).

ALPs would have deep impact in astrophysics and especially in the VHE band whenever magnetic fields are intense and/or the path inside a magnetized medium is long (for an incomplete review see Galanti 2019). In particular, ALPs are produced in the magnetic field of the jet, so modifying BL Lac spectra (see Tavecchio, Roncadelli & Galanti (2015), also later in the text) and explaining FSRQ emission above 20 GeV without placing the emission region far from the center and thus maintaining the validity of classical AGN models (Tavecchio, Roncadelli, Galanti & Bonnoli 2012). When a strong jet magnetic field is considered, $O(1)$G, also the one-loop QED vacuum polarization must be accounted for (Raffelt & Stodolsky 1988); such magnetic field strengths are typical in hadronic models for blazar emission. Inside a galaxy cluster magnetic field, ALPs can produce irregularities in observed spectra which have, however, not been observed yet (Ajello et al. 2016). In extragalactic space photon-ALP oscillations can increase the Universe transparency to VHE photons by mitigating their attenuation via interaction with the photons of the EBL (De Angelis, Galanti & Roncadelli 2011; Galanti & Roncadelli 2018b). Since in extragalactic space the magnetic field $B_{\text{E}}$ is weak, in the range $10^{-17} \lesssim B_{\text{E}} \lesssim 10^{-15} \text{G}$ (e.g. Durrer & Neronov 2013), also the photon dispersion on the cosmic microwave background (CMB) must be taken into account (Dobrynina, Kartavtsev & Raffelt 2015; Galanti & Roncadelli 2018b). Furthermore, photon-ALP oscillations have been employed tentatively to describe better the redshift dependence of AGN spectral indices (De Angelis, Galanti & Roncadelli 2011; Horns & Meyer 2012; Rubtsov & Troitsky 2014; Galanti, Roncadelli, De Angelis & Bignami 2015) and to search for a diffuse flux of photons from ALP-to-photon back-conversion concomitant with neutrino production in extragalactic space (Vogel, Laha & Meyer 2017).

By combining photon-ALP conversion in the source, in extragalactic space and in the Milky Way we can obtain the BL Lac observed spectra modified by the existence of an ALP (Galanti, Tavecchio, Roncadelli & Evoli 2019). Hence, peculiar features arise: oscillations in the spectral energy distribution (SED) and photon excess above 20 TeV. In particular, for far away BL Lacs photon-ALP interaction produces an unexpected peak around 10–30 TeV, which is several orders of magnitude higher than conventional physics predic-
tions. Thus, the analysis of BL Lac spectral features represents one of the best environments among the many studied for ALP physics to detect eventually such an ALP. A final remark is needed. Photon-ALP conversion inside the source depends only on the value of the jet magnetic field but it is independent of the particular state of the BL Lac: thus, the photon-ALP model can be applied equally well both to steady state and to flaring BL Lacs, contrary to the hadron beam model. As a result, we can apply ALP-induced modification to BL Lac spectra to all considered sources: Markarian 501, 1ES 0229+200 and the two BL Lacs similar to 1ES 0229+200 but located at redshifts $z = 0.3$ and $z = 0.5$.

4 LORENTZ INVARIANCE VIOLATION

Many attempts to extend General Relativity to a quantum theory of gravity predict Lorentz invariance violation (LIV) beyond a very high energy scale $E_{\text{LIV}}$. Depending on the model parameters, LIV turns out to possess a very rich phenomenology modifying standard physics interactions and also allowing for otherwise forbidden processes, such as: photon decay, vacuum Cherenkov effect, shifting of existing threshold reactions, photon splitting (Liberati 2013). Many sectors of the SM are affected by LIV-induced modified dispersion relations: recently, LIV impact on neutrino oscillations has been studied in Antonelli, Miramonti & Torri (2018) by using the approach originally introduced by Coleman & Glashow (1999).

Here, we are interested in LIV consequences for photon propagation that translate into a photon modified dispersion relation that contains additional terms in the form of $E^{n+2}/E_{\text{LIV}}^{n}$ where $E$ represents the photon energy (see e.g. Kifune 1999). Limiting to the case $n = 1$, the modified dispersion relation for photons reads

$$E^2 - p^2 = -\frac{E^3}{E_{\text{LIV}}}^2,$$ (2)

where $p$ is the photon momentum. The term in the right hand side of Eq. (2) $m^2_{\gamma,\text{eff}} = -E^2/E_{\text{LIV}}$ formally represents a photon effective mass term which induces a modification in the threshold of the process $\gamma \gamma \rightarrow e^+ e^-$. Once the parameter $E_{\text{LIV}}$– which is of the order of the Planck energy – is fixed, the effect of $m^2_{\gamma,\text{eff}}$ is more and more dramatic as the energy grows as can be inferred from Eq. (2). Although the calculation of the optical depth associated with the process $\gamma \gamma \rightarrow e^+ e^-$ and accounting for the LIV effect is not trivial and possesses some uncertainties coming from different possible assumptions (Fairbairn et al. 2014; Jacob & Piran 2008), the final result is not deeply affected by such uncertainties. Therefore, it is possible to state that the modifications induced by the LIV start to be sizable for $E \gtrsim O(10 \text{TeV})$: the resulting effective transparency turns out to be larger than the standard one (Tavecchio & Bonnoli 2016). Since such modifications are expected for $E \gtrsim O(10 \text{TeV})$ the best astrophysical sources to test such a scenario appear to be high-frequency peaked BL Lacs (HBLs) and extreme BL Lacs (EHBs) since their observed spectra extend to few TeV (Stechler & Glashow 2001; Tavecchio & Bonnoli 2016). As in the case of photon-ALP oscillations, LIV effects on photon transparency are totally independent of the particular state or characteristics of the BL Lacs. Consequently, the LIV model can be applied both to steady state and to flaring BL Lacs, unlike the hadron beam model. Thus, we analyze LIV-induced modifications to the high-energy spectra of Markarian 501, 1ES 0229+200 and two BL Lacs similar to 1ES 0229+200 but placed at redshifts $z = 0.3$ and $z = 0.5$.

5 ANALYSIS OF MODIFIED BL LAC SPECTRA

In this section, we describe the effects of the hadron beam, the photon-ALP oscillations and LIV on BL Lac spectra and we compare the three scenarios, pointing out phenomenological analogies and differences in order to clarify how present and future observational data might detect a hint for new physics coming from one of these three models and how to discriminate among them. Therefore, we analyze hereafter the best candidates for these purposes since they present a very powerful spectrum up to above $10 \text{TeV}$: Markarian 501, 1ES 0229+200 and two BL Lacs similar to 1ES 0229+200 but placed at redshifts $z = 0.3$ and $z = 0.5$. As benchmark values we take $m_a = 10^{-10}$ eV and $g_{\gamma \gamma} = 10^{-11}$ GeV$^{-1}$ for the photon-ALP model and $E_{\text{LIV}} = 10^{20}$ GeV for the LIV scenario (Lang, Martínez-Huerta & de Souza 2019). As far as the EBL is concerned, we employ the model by Franceschini & Rodighiero (2017).

5.1 Markarian 501

Markarian 501 is a nearby and luminous HBL at a redshift $z = 0.34$. Although its quiescent states have been studied as a possible environment where to discover signals of new physics (Fairbairn et al. 2014), active states of Markarian 501 are certainly the best ‘laboratory’ for such an issue (Tavecchio & Bonnoli 2016). In this fashion, the observational data points from HEGRA (Aharonian et al. 2001) represent one of the best examples present in the literature which we use in the following: its high state reaches energies up to above $10 \text{TeV}$ with a hard spectrum (see also the recent high state detected by HESS, Abdalla et al. 2019). As already mentioned above, the hadron beam scenario cannot be applied in this case because of the variability of the source: thus, we concentrate here on photon-ALP interaction and LIV effects of the spectrum of Markarian 501, as reported in Fig. 1. We take a jet magnetic field with a toroidal geometry that assumes the value $B_{\text{jet}} = 0.5$ G in the emission region and we assume a bulk Lorentz factor $\Gamma = 15$ (see also Tavecchio, Roncadelli & Galanti 2015). We envisage that the emission mechanism for this source is leptonic and of the Synchrotron Self-Compton (SSC) type.

For this source we model the intrinsic spectrum with an exponentially truncated power law with energy index $\alpha_1 = 1$ and cutoff energy $E_{\text{cut}} = 20$ TeV. Fig. 1 shows that, as expected from Galanti, Tavecchio, Roncadelli & Evoli (2019), photon-ALP oscillations induce an energy-dependent behaviour of the spectrum and a photon excess for energies above $\sim 20 \text{TeV}$ as compared to conventional physics expectations. In agreement with Tavecchio & Bonnoli (2016), LIV causes an hardening of the observed spectrum for energies above $\sim 20 \text{TeV}$ in a similar way as photon-ALP interactions but LIV predicts also a possible minimum in the spectrum.
5.2 1ES 0229+200

1ES 0229+200 represents the prototype of EHBLs and possesses a hard TeV observed spectrum extending above 10 TeV (Aharonian et al. 2007) in spite of the fact that it is located at a redshift \( z = 0.1396 \), where EBL absorption in the TeV energy range is huge (optical depth \( \tau \gtrsim 2 \), e.g. Franceschini & Rodighiero 2017). EHBLs have peculiar and not yet completely understood features which differentiate them from other BL Lacs. As far as the VHE spectrum is concerned, its extreme hardness challenges standard one-zone leptonic models (see e.g. Tavecchio et al. 2009) and its weak variability is untypical for the BL Lac population (see e.g. Aliu et al. 2014).

In Fig. 2 we show the spectrum of 1ES 0229+200 modified by the inclusion of the hadron beam, photon-ALP and LIV effects, when we consider a jet toroidal magnetic field with a value \( B_{\text{jet},0} = 0.5 \) G in the emission region and a bulk Lorentz factor \( \Gamma = 15 \). These values are found when the emission is modeled with the hadronic scenario of the proton-synchrotron type (see e.g. Cerruti, et al. 2015) – for simplicity we call this scenario ‘high magnetic field case’. In Fig. 3 we consider the same jet magnetic field behaviour but we take \( B_{\text{jet},0} = 2 \) mG and \( \Gamma = 50 \) by assuming a leptonic SSC.
Intrinsic exponentially truncated spectrum but possibly detectable for an intrinsic broken power law one by considering the predicted sensitivity of the CTA (Acharyya et al. 2019). The other features induced by the three models appear to be detectable with an observational exposure of 50h.

In Fig. 3 we take the same intrinsic spectra as in Fig. 2. Everything we have observed in Fig. 2 extends to Fig. 3 concerning the hadron beam and the LIV scenario. We note instead a modification of the spectrum induced by the photon-ALP oscillations: in the 'low magnetic field case' the conversion inside the source is not very efficient and the hard tail in the observed spectrum is greatly reduced. In this case, the most evident imprinting of the photon-ALP interaction is the still remaining peculiar energy-dependent behaviour of the spectrum. The photon-ALP model is almost identical in the cases of both exponentially truncated (upper panel of Fig. 3) and broken power law (lower panel of Fig. 3) intrinsic spectrum.

The observation alone of a harder spectrum above $\sim 10\,\text{TeV}$ as compared to conventional physics predictions could be produced either by the hadron beam or by the photon-ALP oscillation model in the 'high magnetic field case'. The smoking gun to distinguish between the two scenarios is again the eventual detection of energy-dependent oscillations in the observed spectrum since this feature is driven only by the photon-ALP oscillation scenario. Instead, only LIV can reproduce an eventual detection around $\sim 100\,\text{TeV}$.

### 5.3 Extreme BL Lacs at $z = 0.3$ and $z = 0.5$

Due to the observation of BL Lacs up to above a redshift $z \geq 0.5$ we speculate on the existence of EHBLS at redshifts $z = 0.3$ and $z = 0.5$. We assume characteristics similar to the prototype of EHBLS, 1ES 0229+200, but more extreme with respect to the cutoff or break energy. In particular, we use $E_{\text{cut}}$ a factor 2 larger that partially compensates for the enhanced EBL absorption.

In Fig. 4 and Fig. 5 we report the spectrum of the considered BL Lac at redshift $z = 0.3$ when the hadron beam, photon-ALP interaction and LIV effects are taken into account in the case of both the 'high magnetic field case' (Fig. 4) and 'low magnetic field case' (Fig. 5) with the same parameters of 1ES 0229+200.

In the upper panel of Fig. 4 for the intrinsic spectrum we use an exponentially truncated power law with energy index $\alpha_1 = 0.4$ and cutoff energy $E_{\text{cut}} = 15\,\text{TeV}$. In the lower panel we use a broken power law with different parameters for the photon-ALP conversion scenario and the LIV model: we have energy index $\alpha_{1,\text{ALP}} = 0.6$ and $\alpha_{1,\text{LIV}} = 0.4$, high-energy index $\alpha_{2,\text{ALP}} = 2.2$ and $\alpha_{2,\text{LIV}} = 2$ and break energy $E_{\text{b,ALP}} = E_{\text{b,LIV}} = 10\,\text{TeV}$. From Fig. 2 we observe that the hadron beam scenario produces a hard tail above $\sim 10\,\text{TeV}$ extending monotonically up to above $100\,\text{TeV}$ as already reported in Tavecchio, Romano, Landoni & Vercellone (2019). In agreement with Galanti, Tavecchio, Roncadelli & Evoli (2019) photon-ALP oscillations produce an energy-dependent behaviour of the spectrum and a sizable photon excess above $\sim 10\,\text{TeV}$ both when the intrinsic spectrum is an exponentially truncated power law and even more when it is a broken power law. As expected from Tavecchio & Bonnoli (2016), LIV-induced modifications on the spectrum are negligible around $\sim 10\,\text{TeV}$ but they predict a peak around $\sim 100\,\text{TeV}$ that is hardly observable in the case of an enhanced EBL absorption.

The assumed intrinsic spectra in Fig. 5 are the same as Fig. 2 but we take $B_{\text{jet,0}} = 2\,\text{mG}$ and $\Gamma = 50$. See the text for more details.
of Fig. 4. As for 1ES 0229+200, the hadron beam and the LIV scenario effects in Fig. 5 are the same as in Fig. 4. Concerning the photon-ALP interaction, the ‘low magnetic field case’ of Fig. 5 shows that the conversion inside the source is low thus not allowing for the production of a peak in the observed spectrum around 20–30 TeV as predicted instead in the ‘high magnetic field case’ of Fig. 4. In the ‘low magnetic field case’ of Fig. 5 the hard tail up to ~10 TeV still remains. Again, the signature of the photon-ALP interaction is the persisting peculiar energy-dependent behaviour of the spectrum. The different choice of the intrinsic spectrum with an exponentially truncated (upper panel of Fig. 5) and broken power law (lower panel of Fig. 5) does not significantly affect the predictions of the photon-ALP model.

We observe in Fig. 4 that the hadron beam and the photon-ALP interactions produce a similar hardening in the observable spectrum up to ~10 TeV and once more the detection/absence of energy-dependent oscillations in the spectrum would represent the possibility to distinguish between the two models. For the considered BL Lac at redshift $z = 0.3$ the hard tail up to ~10 TeV predicted both by the hadron beam and by the photon-ALP interaction is of the order of the CTA sensitivity and thus believed as observable. In addition, we expect that the peak predicted by the photon-ALP scenario around 20–30 TeV in the ‘high magnetic field case’ could be detected in the near future by the CTA (Acharyya et al. 2019). Since other considered scenarios do not predict a peak at these energies, an eventual detection of photons at 20–30 TeV would represent a smoking gun for the existence of an ALP. Although it appears less likely, a detection at energies above 100 TeV would be a strong indication of LIV effects (with an intrinsic broken power law spectrum) since other models are unable to reach efficiently such energies (only partially this may be the case for photon-ALP interaction with an intrinsic broken power law spectrum).

Everything we have stated for the $z = 0.3$ case translate to the case of a BL Lac at redshift $z = 0.5$, whose new-physics-induced modified spectra are reported in Fig. 6 for the ‘high magnetic field case’ and in Fig. 7 for the ‘low magnetic field case’. All parameters here are the same chosen for the case $z = 0.3$. In any case, for such a far source the real detectability of these features remains problematic even for energies below ~1 TeV. Instead, the peak predicted by the photon-ALP scenario around 20–30 TeV in the ‘high magnetic field case’ is expected to be observable by the CTA (Acharyya et al. 2019) – which would unequivocally be associated with the existence of an ALP since other processes are unable to produce a similar peak. Instead, the detection of photons at energies above 100 TeV would represent a rather robust hint at LIV effects (with an intrinsic broken power law spectrum) since photon-ALP interaction with an intrinsic broken power law spectrum might only partially produce consequences at such energies and the hadron beam scenario totally fails in this respect. However, such a detection – already challenging in the case $z = 0.3$ – is considered as prohibitive in the case $z = 0.5$ even for the CTA capabilities.

Figure 4. Same as Fig. 2 but for a BL Lac at $z = 0.3$. In this case for both the photon-ALP interaction and the LIV scenario we take the same parameters concerning the intrinsic exponentially truncated power law upper panel and the broken power law (lower panel) spectrum. We take $B_{\text{jet},0} = 0.5$ G and $\Gamma = 15$. See the text for more details.

6 CONCLUSIONS

In this paper, we have analyzed the effects of the hadron beam scenario, photon-ALP oscillations and LIV on BL Lac spectra. We have concentrated on an archival high state of Markarian 501 and on 1ES 0229+200 since they represent the best candidates for a search for new physics signatures. In addition, we have considered two hypothetical EHBLs at redshifts $z = 0.3$ and $z = 0.5$.

The hadron beam scenario – which is not applicable to the high state of Markarian 501 because of the source high variability – gives rise to a hard tail with respect to conventional physics for observed BL Lac spectra. A similar photon excess is predicted in the ‘high magnetic field case’ by the photon-ALP interaction model but the two scenarios can be distinguished by searching for energy-dependent oscillations in the observed spectrum since they may be induced only by photon-ALP interaction. LIV gives rise to a peak in the spectra at energies around ~100 TeV for both close and far-
away sources while a strong peak is predicted in the ‘high magnetic field case’ by photon-ALP oscillations for farther sources only and at slightly lower energies ($\sim 20 - 30$ TeV). In any case, the concomitant detection of energy oscillations in the spectrum would be the smoking gun for the photon-ALP interactions. As is evident from all figures, the amplitude of the photon-ALP induced energy oscillations in the spectrum becomes bigger and bigger as the redshift of the source grows: the reason is that the photon-ALP beam is sensitive to all crossed magnetized media. Thus, a more distant source crosses many different magnetic field structures and this fact amplifies the variation of the oscillation amplitude since the photon-ALP system keeps memory of all crossed magnetized media.

As a side note, we remark that the ALP identification through the detection of energy-dependent oscillations in the observed spectrum may represent, at least in principle, a unique opportunity to infer also information about the emission mechanism of BL Lacs. Since the efficiency of the photon-ALP conversion is strictly related to the intensity of the magnetic field crossed by the photon-ALP beam, a very hard tail above $\sim 20$ TeV observed for 1ES 0229+200 would imply a very high value for the magnetic field in the jet, suggesting a hadronic emission mechanism. Instead, the absence of a hard tail above $\sim 20$ TeV would be related to a lower value for the magnetic field in the jet, suggesting a leptonic SSC emission mechanism. A similar conclusion may be achieved about the hypothetical sources at redshifts $z = 0.3$ and $z = 0.5$: here, the distinction is represented by the presence/absence of a peak in the observed spectrum at $\sim 20 - 30$ TeV. The eventual observation of the peak – associated with a high value of the magnetic field in the jet – would be an indication for a hadronic emission mechanism, while its absence would imply a preference for a leptonic SSC emission mechanism compatible with lower values of the jet magnetic field.

As far as the real detectability of such features is concerned, we stress that, although Markarian 501 and 1ES 0229+200 are northern sources, we show for all BL Lacs the CTA south sensitivity (where such sources are observable with a large zenith angle). The reason for this choice is that, since we are interested in non-SM effects in the TeV and multi-TeV range, as a matter of fact, the best telescopes suitable for these observations are the SSTs (Small-Sized

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**Figure 5.** Same as Fig. 4 but we take $B_{\text{jet},0} = 2$ mG and $\Gamma = 50$. See the text for more details.

**Figure 6.** Same as Fig. 4 but for a BL Lac at $z = 0.5$. See the text for more details.
Figure 7. Same as Fig. 5 but for a BL Lac at $z = 0.5$. See the text for more details.

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