PROCEEDINGS OF SCIENCE

Inverse Compton scattering from Bethe-Heitler pairs as a plausible origin of hard spectra in flaring TeV blazars: 1ES 0414+009 and 1ES 1959+650

Samuel Victor Bernardo da Silva,[a] **Luiz Augusto Stuani Pereira**[a,b,*] **and Rita de Cássia dos Anjos**[c]

[a] *Unidade Acadêmica de Física, Universidade Federal de Campina Grande (UFCG), R. Aprígio Veloso, 882, Campina Grande, Brazil*

[b] *Instituto de Física, Universidade de São Paulo (USP), R. do Matão, 1371, São Paulo, Brazil*

[c] *Departamento de Engenharias e Exatas, Universidade Federal do Paraná (UFPR), R. Pioneiro, 2153, Palotina, Brazil*

E-mail: luizstuani@uaf.ufcg.edu.br

Blazars are a special subclass of active galactic nuclei (AGNs) characterized by a relativistic jet aligned at a small angle to the observer's line of sight. Their spectral energy distributions (SEDs) are dominated by non-thermal emission and exhibit two broad, distinct components: a low-energy component, spanning from radio to UV or X-ray wavelengths, and a high-energy component, extending from X-ray to γ-ray energies. It is widely believed that the low-energy emission in blazar SEDs originates from synchrotron radiation produced by relativistic electrons within the jet. However, the origin of the high-energy component remains a subject of debate. Two primary theoretical models attempt to explain this emission: i) leptonic model: High-energy photons are generated via inverse Compton scattering, where relativistic electrons interact with a surrounding photon field. Potential soft photon sources include synchrotron photons produced within the jet itself, known as synchrotron self-Compton (SSC) emission; and ii) Hadronic Model: High-energy emission arises from proton synchrotron radiation or from secondary emission produced by proton–proton (pp) and proton–photon (pγ) interactions. In this work, we model the SEDs of high-frequency-peaked BL Lac objects (HBLs): 1ES 0414+009 and 1ES 1959+650. The hard γ-ray spectra of these sources suggest the possible contribution of an additional spectral component beyond the standard SSC emission, indicating a more complex emission mechanism at play. We propose the hard γ-ray spectrum for the blazars may originate from inverse Compton scattering from Bethe-Heitler pairs along the line of sight.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

1. Introduction

Blazars are a class of radio-loud active galactic nuclei (AGN) with relativistic jets oriented close to our line of sight, resulting in strongly beamed non-thermal emission across the entire electromagnetic spectrum [1]. Their broadband spectral energy distributions (SEDs) exhibit a characteristic two-hump structure: the low-energy component, extending from radio to X-rays, is attributed to synchrotron radiation from relativistic electrons; the high-energy component, spanning from MeV to TeV energies, is less well understood and is thought to arise from either leptonic or hadronic processes [2, 3].

Leptonic models explain the high-energy emission through inverse Compton (IC) scattering, either of synchrotron photons produced within the jet (SSC) or of external photons (EC) originating from the broad-line region or dusty torus [4, 5]. In contrast, hadronic models invoke proton synchrotron radiation or cascades triggered by proton–photon or proton–proton interactions to account for the gamma-ray output [6, 7]. An additional contribution can arise from Bethe-Heitler pair production, though it is typically subdominant [8].

BL Lac objects are often classified based on their synchrotron peak frequency (ν_p^S): low-frequency peaked BL Lacs (LBLs, $\nu_p^S < 10^{14}$ Hz), intermediate (IBLs, $10^{14} < \nu_p^S < 10^{15}$ Hz), and high-frequency peaked BL Lacs (HBLs, $\nu_p^S > 10^{15}$ Hz) [2]. HBLs are especially relevant for TeV studies, as their SEDs often peak in the VHE range and are well modeled by SSC scenarios [5, 9].

The physical origin and dynamics of relativistic jets remain active areas of research. Magnetic fields are thought to play a central role in jet launching and energy conversion, whether through the extraction of rotational energy from a spinning black hole (Blandford-Znajek mechanism) or from the accretion disk (Blandford-Payne mechanism) [10, 11]. Estimating jet magnetic fields through core-shift measurements or SED modeling is critical to understanding these processes [3, 12].

In this work, we investigate the SEDs of two TeV blazars, 1ES 0414+009 and 1ES 1959+650, using multiwavelength data to constrain their jet parameters and explore the role of leptonic and hadronic emission mechanisms [1]. The structure of the paper is as follows: Section 2 describes the sources; Sections 3 and 4 outline the modeling tools and procedures; Section 5 presents results and discussion; and Section 6 offers concluding remarks. We adopt a flat ΛCDM cosmology with $H_0 = 67.77$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$.

2. TeV Blazars: 1ES 0414+009 and 1ES 1959+650

In this section, we provide a brief overview of the two TeV blazars analyzed in this study, along with a description of the data sets used in our analysis.

2.1 1ES 0414+009

1ES 0414+009 is a high-frequency peaked BL Lac at redshift 0.287, first detected in X-rays and later identified with the Einstein Observatory [14]. Powered by a supermassive black hole, it exhibits synchrotron emission peaking in the UV to soft X-ray range [15]. Although early observations only set flux limits, H.E.S.S. later detected faint very-high-energy gamma-ray emission at around 0.6%

[1] These results and their graphical representations have already been discussed in detail by Bernardo da Silva et al. (2025) [13].

of the Crab Nebula flux above 200 GeV [16]. Its high-energy spectra challenge standard emission models and suggest complex particle acceleration processes [17]. The source is also considered a candidate for ultra-high-energy cosmic rays and plays a role in AGN studies [18].

2.2 1ES 1959+650

1ES 1959+650 is a BL Lac object at redshift 0.047, first detected at TeV energies in 1998 and later exhibiting a major outburst in 2002, reaching flux levels up to three times that of the Crab Nebula [19, 20]. Classified as HBL, it is usually faint and less variable in the Fermi-LAT range, though notable flares occurred between 2015 and 2016 [21]. Its hard X-ray and gamma-ray spectra during flaring periods challenge standard leptonic models, with hadronic scenarios like the proton blazar model offering alternative explanations, though leptonic interpretations are still commonly favored [5, 22].

3. Multiwavelength SED fitting of jetted AGN

To model the SEDs of 1ES 0414+009 and 1ES 1959+650, we employed the open-source tools JetSeT [23] for leptonic scenarios and AM^3 [24] for lepto-hadronic ones. JetSeT implements a one-zone synchrotron and synchrotron self-Compton (SSC) model, where relativistic electrons, described by a broken power-law distribution [5], radiate within a spherical region moving along the jet with Doppler factor δ, and model fitting is performed via phenomenological SED fitting and Bayesian inference using MCMC sampling [25]. In the lepto-hadronic framework of AM^3, the emission region is also modeled as a spherical blob moving with bulk Lorentz factor Γ, where electrons and protons are injected isotropically; protons, following a power-law distribution, interact with ambient photons to produce pions that decay into gamma rays, neutrinos, and secondary leptons, fueling electromagnetic cascades [26]. AM^3 self-consistently includes processes such as synchrotron emission and absorption, inverse Compton scattering, Bethe–Heitler pair production, photon-photon interactions, and secondary particle evolution in a turbulent magnetic field, shaping both the SED and potential multi-messenger signals.

4. Results and Discussions

To model the non-thermal multiwavelength emission of blazars, data from radio to very-high-energy gamma-rays were obtained from the Space Science Data Center (SSDC) and Firmamento. The observations were first fitted with JetSeT using MCMC to find the best parameters, which were then used as input for the lepto-hadronic modeling with AM^3. The best-fitting values are described in Table 1.

Lepto-hadronic SED modeling was done using AM^3, with the electron distributions from JetSeT fits, showing electron luminosities in the jet $\sim 2.50 \times 10^{43}$ erg/s for 1ES 0414+009 and $\sim 3.93 \times 10^{43}$ erg/s for 1ES 1959+650. Proton luminosities were constrained to be less than or equal to the Eddington luminosity ($L_p \leq L_{\rm Edd}$) [27], estimated from black hole masses of about 2×10^9 $M_\odot$ and 3.16×10^8 $M_\odot$. Proton injection followed a simple power-law with minimum and maximum Lorentz factors of 100 and one million, respectively, and a spectral index of 1. While

Table 1: SSC model parameters for 1ES 0414+009 and 1ES 1959+650.

Symbol	Description	1ES 0414+009	1ES 1959+650
$\gamma_{\rm min}$	Minimum electron Lorentz factor	6.35×10^1	9.60×10^2
$\gamma_{\rm break}$	Break electron Lorentz factor	8.11×10^4	1.96×10^5
$\gamma_{\rm max}$	Maximum electron Lorentz factor	1.70×10^6	2.40×10^6
B [G]	Magnetic field strength	3.62×10^{-1}	1.05×10^{-1}
R [cm]	Radius of emitting region (blob)	1.02×10^{16}	3.15×10^{15}
$\theta_{\rm obs}$ [deg]	Viewing angle	1.61	2.9
N [cm^{-3}]	Particle number density	45.11	12.47
p	Spectral index below $\gamma_{\rm break}$	2.29	2.41
p_1	Spectral index above $\gamma_{\rm break}$	4.45	4.37
Γ	Bulk Lorentz factor	15.02	37.25

super-Eddington jet powers may occur briefly during flares, they are unlikely during steady emission phases.

Figures 1 and 2 show the multiwavelength SEDs of 1ES 0414+009 and 1ES 1959+650 with data from BeppoSAX, VERITAS, *Fermi*-LAT, and others. The dark blue and red lines represent synchrotron and inverse Compton (IC) emission from primary electrons (JetSeT fits), while the black line shows proton synchrotron and IC emission. The light blue line depicts Bethe-Heitler pair production ($p\gamma \to pe^+e^-$), and the green line shows synchrotron and IC emission from secondary electron-positron pairs ($\gamma\gamma \to e^+e^-$). The yellow line corresponds to emission from charged pion decay ($p\gamma \to \pi^\pm \to e^\pm$), and the purple dotted curve represents gamma rays from neutral pion decay ($p\gamma \to \pi^0 \to \gamma\gamma$). Finally, the dark blue dashed line illustrates gamma-ray emission from neutral pion decay via proton-proton interactions ($pp \to \pi^0 \to \gamma\gamma$). Energy ranges vary between the two sources but cover radio to very-high-energy gamma rays.

Figure 1 shows a possible hadronic contribution between 10^8 and 2×10^{12} eV. In this range, IC scattering by secondary $e^\pm$ pairs from Bethe–Heitler processes explains the high-energy bump that matches the *Fermi*-LAT 2FHL flux of 1.78×10^{-11} erg cm^{-2} s^{-1} at 1.08×10^{12} eV [28]. A lower flux of 5.2×10^{-12} erg cm^{-2} s^{-1} at 0.2 GeV, reported in the Fermi 1FGL catalog [29], is attributed to IC emission from secondary electrons produced via muon decay following $p\gamma$ interactions. Both features, highlighted in the figure, support a consistent hadronic interpretation of the source's broadband emission.

Figure 2 reveals a possible hadronic contribution that bridges the gap between the two characteristic broadband emission components. In this interpretation, Bethe–Heitler pair production by ultra-high-energy protons accounts for the X-ray emission in the intermediate region. The resulting secondary electron–positron pairs radiate synchrotron emission that matches the observed X-ray flux. Additionally, the IC component—seen as the high-energy bump in the blue curve—helps reproduce the VHE gamma-ray emission between $\sim 10^{11}$ eV and 10^{14} eV, consistent with Whipple observations during flaring episodes. Notably, on June 4, 2002, 1ES 1959+650 exhibited a strong gamma-ray flare without a corresponding X-ray increase, an "orphan" flare and the first of its kind observed in a blazar [30]. This behavior reinforces the need for a lepto-hadronic modeling approach,

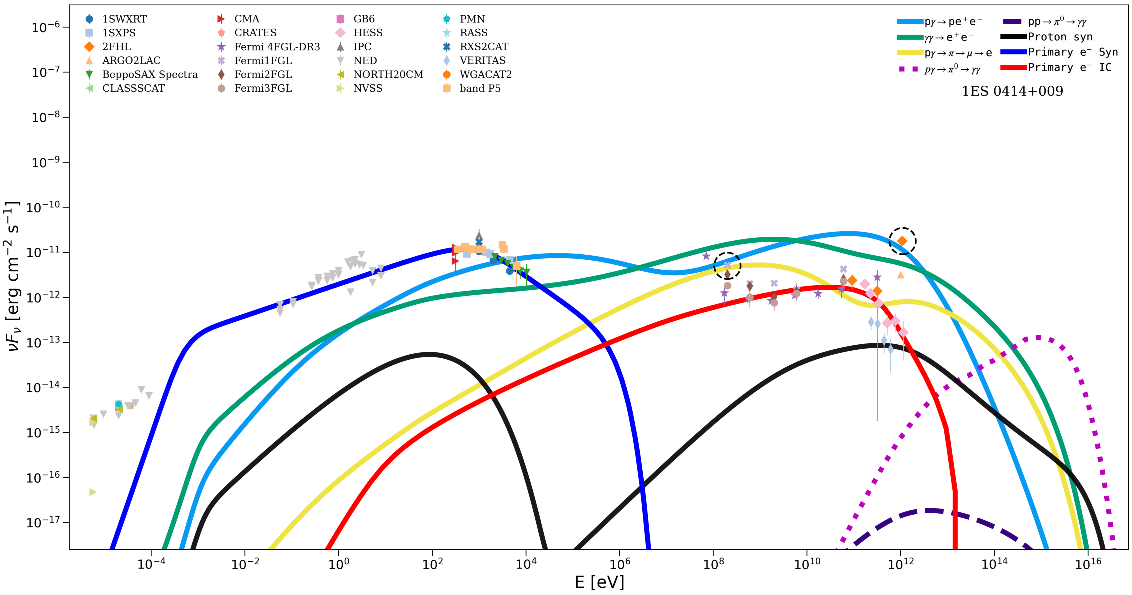

Figure 1: Lepto-hadronic SED modeling and multi-wavelength data of the source 1ES 0414+009. Figure adapted from Bernardo da Silva et al. (2025), Universe, 11, 177 (DOI:10.3390/universe11060177), published under CC BY 4.0 license.

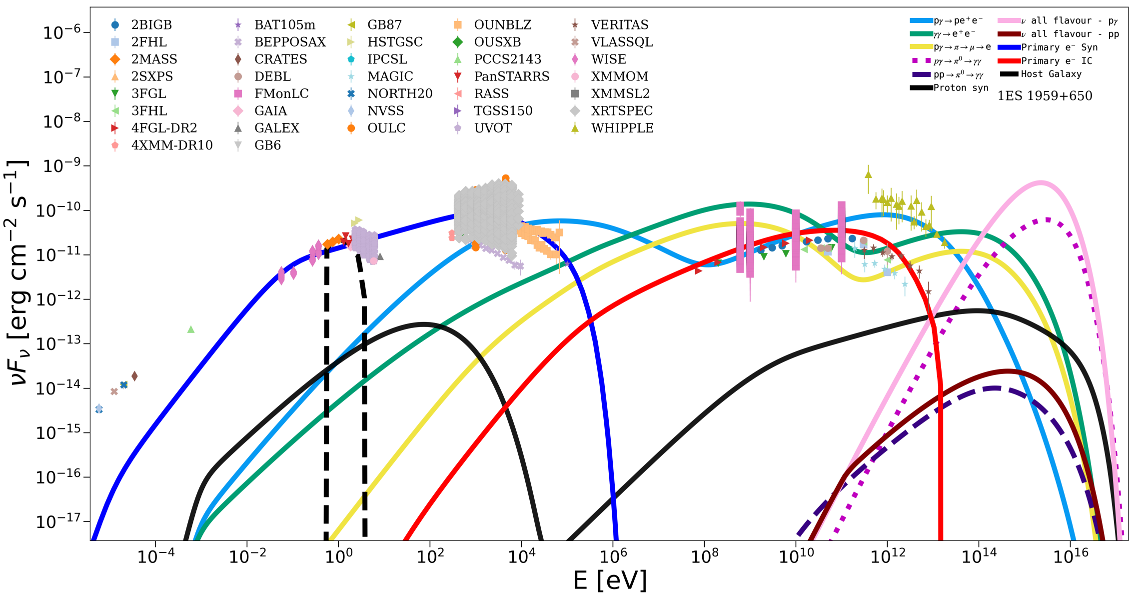

Figure 2: Lepto-hadronic SED modeling and multi-wavelength data of the source 1ES 1959+650. Figure adapted from Bernardo da Silva et al. (2025), Universe, 11, 177 (DOI:10.3390/universe11060177), published under CC BY 4.0 license.

which not only accounts for such high-energy anomalies but also implies the presence of nuclear acceleration processes. These insights have broader implications for future neutrino detections and support the idea that blazar jets are capable of accelerating hadrons to ultra-high energies [31–34].

5. Conclusions

We employed the open-source tools JetSeT and AM^3 to model the SEDs of two high-frequency-peaked BL Lacertae objects (HBLs): 1ES 0414+009 and 1ES 1959+650. The best-fit model parameters were obtained by matching the predicted multi-wavelength emission to publicly available observational data. Initial modeling under a purely leptonic scenario failed to reproduce the observed hard gamma-ray spectra during flaring states, particularly above 10^{11} eV. To address this discrepancy, we extended our analysis to a lepto-hadronic framework, incorporating proton-proton (pp) and proton-photon (pγ) interactions within the jet environment. The inclusion of the pγ component suggests that hadronic processes may significantly contribute to the high-energy emission of both sources during flares. In particular, Bethe–Heitler pair production ($p\gamma \rightarrow p + e^+ + e^-$) effectively accounts for the observed X-ray and VHE gamma-ray fluxes. This mechanism injects secondary electron-positron pairs into the emission region, which radiate via synchrotron emission and IC scattering of soft photons, contributing to the high-energy SED alongside the primary electron population. In summary, the lepto-hadronic model successfully reproduces the broadband emission from both sources, highlighting the necessity of incorporating hadronic processes to achieve a comprehensive description of BL Lac emission, particularly during high-activity states.

References

[1] C. M. Urry and P. Padovani, *Unified Schemes for Radio-Loud Active Galactic Nuclei*, *Publ. Astron. Soc. Pac.* **107** (1995) 803, doi:10.1086/133630, [astro-ph/9506063].

[2] A. A. Abdo et al., *The spectral energy distribution of Fermi bright blazars*, *Astrophys. J.* **716** (2010) 30, doi:10.1088/0004-637X/716/1/30.

[3] G. Ghisellini et al., *General physical properties of bright Fermi blazars*, *Mon. Not. Roy. Astron. Soc.* **402** (2010) 497, doi:10.1111/j.1365-2966.2009.15898.x.

[4] C. D. Dermer and R. Schlickeiser, *Model for the High-Energy Emission from Blazars*, *Astrophys. J.* **416** (1993) 458, doi:10.1086/173251.

[5] F. Tavecchio et al., *TeV BL Lac objects at the dawn of the Fermi era*, *Mon. Not. Roy. Astron. Soc.* **401** (2010) 1570, doi:10.1111/j.1365-2966.2009.15784.x.

[6] F. A. Aharonian, *TeV gamma rays from BL Lac objects due to synchrotron radiation of extremely high energy protons*, *New Astron.* **5** (2000) 377, doi:10.1016/S1384-1076(00)00039-7.

[7] K. Mannheim, *The proton blazar*, *Astron. Astrophys.* **269** (1993) 67, doi:10.48550/arXiv.astro-ph/9302006.

[8] S. R. Kelner and F. A. Aharonian, *Energy spectra of gamma rays, electrons, and neutrinos produced at interactions of relativistic protons with low energy radiation*, *Phys. Rev. D* **78** (2008) 034013, doi:10.1103/PhysRevD.78.034013.

[9] J. Zhang et al., *Radiation mechanisms and physical properties of GeV–TeV BL Lac objects*, *Astrophys. J.* **752** (2012) 157, doi:10.1088/0004-637X/752/2/157.

[10] R. D. Blandford and R. L. Znajek, *Electromagnetic extraction of energy from Kerr black holes*, *Mon. Not. Roy. Astron. Soc.* **179** (1977) 433, doi:10.1093/mnras/179.3.433.

[11] R. D. Blandford and D. G. Payne, *Hydromagnetic flows from accretion discs and the production of radio jets*, *Mon. Not. Roy. Astron. Soc.* **199** (1982) 883, doi:10.1093/mnras/199.4.883.

[12] M. Zamaninasab et al., *Dynamically important magnetic fields near accreting supermassive black holes*, *Nature* **510** (2014) 126, doi:10.1038/nature13399.

[13] S. V. Bernardo da Silva, L. A. Stuani Pereira, and R. C. dos Anjos, *Bethe–Heitler Cascades and Hard Gamma-Ray Spectra in Flaring TeV Blazars: 1ES 0414+009 and 1ES 1959+650*, *Universe* **11** (2025) 177, doi:10.3390/universe11060177.

[14] J. P. Halpern et al., *The Redshift of the X-ray Selected BL Lacertae Object H0414+009*, *Astron. J.* **101** (1991) 818, doi:10.1086/115725.

[15] P. Padovani and P. Giommi, *A sample-oriented catalogue of BL Lacertae objects*, *Mon. Not. Roy. Astron. Soc.* **277** (1995) 1477, doi:10.1093/mnras/277.4.1477.

[16] F. Volpe et al., *Discovery of VHE and HE emission from the blazar 1ES 0414+009 with H.E.S.S and Fermi-LAT*, arXiv:1105.5114, doi:10.48550/arXiv.1105.5114.

[17] H.E.S.S. Collaboration, *Discovery of hard-spectrum gamma-ray emission from the BL Lacertae object 1ES 0414+009*, *Astron. Astrophys.* **538** (2012) A103, doi:10.1051/0004-6361/201118406.

[18] V. A. Acciari et al., *New Hard-TeV Extreme Blazars Detected with the MAGIC Telescopes*, *Astrophys. J. Suppl.* **247** (2020) 16, doi:10.3847/1538-4365/ab5b98.

[19] T. Nishiyama et al., Proc. 26th Int. Cosmic Ray Conf. (ICRC), Salt Lake City **3** (1999) 370.

[20] F. Aharonian et al., *Detection of TeV gamma-rays from the BL Lac 1ES 1959+650 in its low states and during a major outburst in 2002*, *Astron. Astrophys.* **406** (2003) L9, doi:10.1051/0004-6361:20030838.

[21] B. Kapanadze et al., *The TeV blazar 1ES 1959+650 – a short review*, PoS(ICRC2017) **306** (2018) 033, doi:10.22323/1.306.0033.

[22] A. Shukla et al., *Multi-frequency, multi-epoch study of Mrk 501: Hints for a two-component nature of the emission*, *Astrophys. J.* **798** (2014) 2, doi:10.1088/0004-637X/798/1/2.

PoS(ICRC2025)850

[23] A. Tramacere, *JetSeT: Numerical modeling and SED fitting tool for relativistic jets*, *Astrophysics Source Code Library, record ascl:2009.001*, https://ui.adsabs.harvard.edu/abs/2020ascl.soft09001T.

[24] M. Klinger et al., *AM^3: An Open-source Tool for Time-dependent Lepto-hadronic Modeling of Astrophysical Sources*, *Astrophys. J. Suppl.* **275** (2024) 4, doi:10.3847/1538-4365/ad725c, [arXiv:2312.13371].

[25] D. Foreman-Mackey et al., *emcee: The MCMC Hammer*, *Publ. Astron. Soc. Pac.* **125** (2013) 306, doi:10.1086/670067, [arXiv:1202.3665].

[26] S. Hümmer et al., *Simplified models for photohadronic interactions in cosmic accelerators*, *Astrophys. J.* **721** (2010) 630, doi:10.1088/0004-637X/721/1/630.

[27] X. Rodrigues et al., *Leptohadronic multi-messenger modeling of 324 gamma-ray blazars*, *Astron. Astrophys.* **681** (2024) A119.

[28] M. Ackermann et al., *2FHL: The Second Catalog of Hard Fermi-LAT Sources*, *Astrophys. J. Suppl.* **222** (2016) 5.

[29] A. A. Abdo et al., *Fermi Large Area Telescope First Source Catalog*, *Astrophys. J. Suppl.* **188** (2010) 405.

[30] H. Krawczynski et al., *Multiwavelength Observations of Strong Flares from the TeV Blazar 1ES 1959+650*, *Astrophys. J.* **601** (2004) 151, doi:10.1086/380393.

[31] N. Sahakyan, *Lepto-hadronic γ-Ray and Neutrino Emission from the Jet of TXS 0506+056*, *Astrophys. J.* **866** (2018) 109, doi:10.3847/1538-4357/aadade.

[32] E. Aguilar-Ruiz, A. Galván-Gámez and N. Fraija, *Testing a Lepto-Hadronic Two-Zone Model with Extreme High-Synchrotron Peaked BL Lacs and Track-like High-Energy Neutrinos*, *Galaxies* **11** (2023) 117, doi:10.3390/galaxies11060117.

[33] E. Aguilar-Ruiz, N. Fraija and A. Galván-Gámez, *High-energy neutrino fluxes from hard-TeV BL Lacs*, *J. High Energy Astrophys.* **38** (2023) 1, doi:10.1016/j.jheap.2023.02.001.

[34] R. Sasse, R. Costa Jr., L. A. Stuani Pereira and R. C. dos Anjos, *Blazars Jets and Prospects for TeV-PeV Neutrinos and Gamma Rays Through Cosmic-Ray Interactions*, *Braz. J. Phys.* **55** (2025) 60, doi:10.1007/s13538-024-01689-3, arXiv:2501.09108.