Data-driven extrapolation schemes of *Fermi*-LAT spectra to the VHE

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Abstract

After 10 years of operations of the Large Area Telescope (LAT), a high-energy pair-creation telescope onboard the Fermi satellite, the Fermi Collaboration has produced two major catalogs: the 4FGL and the 3FHL. These catalogs represent the best sample of potential very high energy (VHE) emitters that may be studied by Imaging Atmospheric Cherenkov Telescopes (IACTs). Several methods are used to extrapolate the Fermi-LAT spectra to TeV energies, generally using simple analytical functions. The recent success of IACTs has motivated the creation of catalogs listing the discoveries of these experiments. Among these initiatives, gamma-cat excels as an open-access tool to archive high-level results in the VHE field, such as catalogs, spectra and light curves. By using these resources, we present a data-driven methodology to test the reliability of different VHE extrapolation schemes used in the literature and evaluate their accuracy reproducing real VHE observations.

Main Objectives

Blazars are radio-loud AGNs with jets closely aligned with the line of sight. They can be classified according to the frequency of the Synchrotron emission maximum in: i) LSP: $\nu_{Sy,peak} < 10^{14}$ Hz ii) ISP: $\nu_{Sy,peak} \in [10^{14}, 10^{15}]$ Hz, iii) HSP: $\nu_{Sy,peak} \in [10^{15}, 10^{17}]$ Hz, iv) EHSP: $\nu_{Sy,peak} > [10^{17}]$ Hz,

Blazar observations with IACTs are often driven by external triggers and therefore biased toward high states. Also, only about ~ 80 blazars have been detected in VHE (TeVCat [1] as of April 2021). Two ways have been proposed to explore what the VHE extragalactic sky looks like:

- Deep VHE blazar observations during low-states.
- Using extrapolations from HE spectra.

In [2], an extrapolation scheme is proposed to explore the second option, by using a Log-Parabola spectrum for all blazars with a physics-driven cut-off, which depended on: i) redshift: [$E_{cut} = E'_{cut}/(1+z)$]; ii) type of source: $E'_{cut} = 100\,\mathrm{GeV}$ for LSP/ISP, $1\,\mathrm{TeV}$, $10\,\mathrm{TeV}$ for EHSP.

This work presents a tool to systematically test different extrapolation schemes often applied in the field, using for that real observations in VHE.

Extrapolation of HE data to the TeV energies

In order to test extrapolation schemes on a systematic way, we created the tool `Ext2TeV` to test how extrapolated HE data from LAT reproduces observed VHE emission.

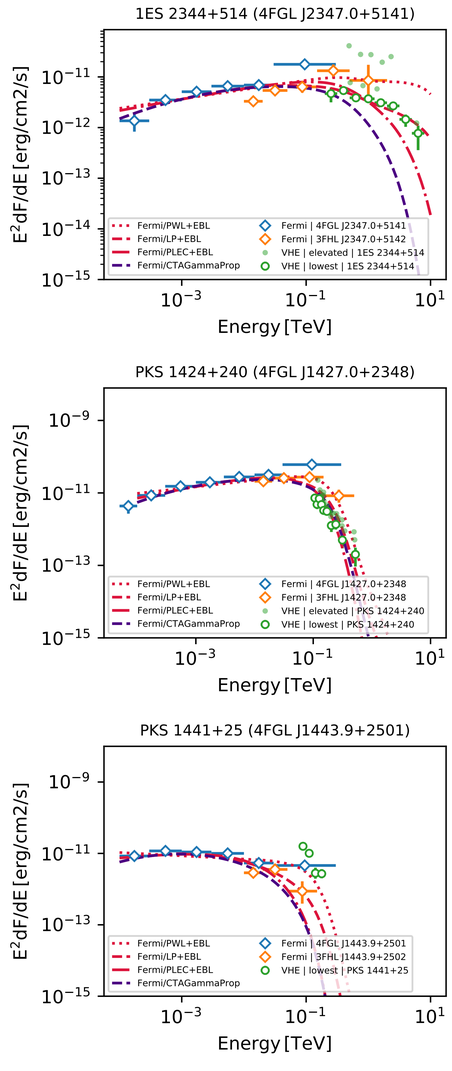
Method

1. Load available HE and VHE blazar catalog data:
   (a) HE: 4FGL, 4LAC and 3FHL (redshifts from 4LAC).
   (b) VHE: GammaCAT[3] and VTSCat[4].
2. For each VHE source, find the HE counterpart.
3. Identify the lowest published state in VHEs.
4. Systematically test common spectral shapes (all shapes include EBL absorption from [5]):
   (a) Power Law (PWL)
   (b) Log Parabola (LP)
   (c) Power Law with sub-exponential cut-off (PLEC).
   (d) "CTAGammaProp" extrapolation scheme, from [2].
5. Statistical Analysis: test the residuals (on a log-log Spectral Energy Distribution) as a function of spectral source type (LSP/ISP/HSP/EHSP) and extrapolation scheme.

Results

Broadband γ-ray SED fitting

By using `Ext2TeV`, we systematically test different extrapolations schemes to model publicly available broadband γ-ray blazar emission. Figure 1 shows 4 different examples. As shown in Fig. 1, extrapolations work differently for different blazars.



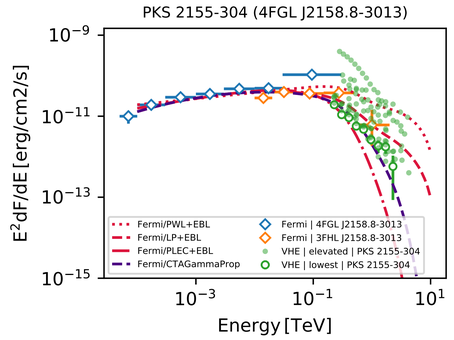


Figure 1: Spectral energy distributions for four VHE blazars. Title shows the common name of the source and the 4FGL catalog name (in parenthesis). In blue and orange open diamonds we show the Fermi 4FGL and 3FHL spectral points. Green open circles show the lowest state recorded in the VHE catalogs. Green filled dots show elevated states from the same source. The different extrapolations considered in this work are shown in dashed and dotted curves.

Statistical analysis: Blazar classes

This works considers 43 AGNs in total. They are classified according to the position of the synchrotron emission maximum, as recorded in the 4FGL catalog. 25 are HSP blazars, followed by ISPs and LSPs (11). Only 2 sources are classified as extreme HSPs and 5 remain unclassified.

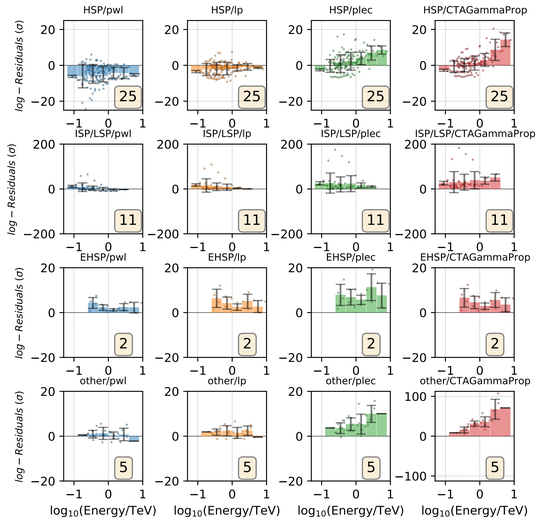


Figure 2: Statistical analysis of the spectral residuals for different extrapolation schemes and source classes.

The analysis of residuals for different extrapolation and blazar classes is shown in Figure 2, concluding:

- VHE emission from HSPs is best reproduced with a LP. A PWL results on an overestimation of VHE flux, while models considering exponential cut-offs yield too low VHE fluxes.
- The rest of the classes seem to favor the PWL extrapolation. However, this is likely due to lower statistics combined with many LSP/ISPs (including FSRQs) being only detectable in elevated states.

Future improvements

This works relies on publicly-available results by the current generation of IACTs, gathered in the form of catalogs. Therefore, these results will improve the more statistics we are able to include.

- *HE* catalogs published by *Fermi*-LAT contain most of the sources ever detected in that band, however dominated by an average state (over several years).
- For *VHE*, many sources have been detected in different states of activity but not all of these states have been published. In addition, many of these published spectra are not available in machine-readable formats, and were never included into any catalog.

This work is just an example of the potential of gathering publicly available information into catalogs. Efforts exist in producing VHE catalogs, such as *GammaCAT* and *VTSCat*. Major improvements to the results presented here are achievable by making sure existing VHE catalogs keep up to date and complete, in addition to the VHE blazar studies performed by current and future IACT collaborations.

Conclusions

- AGN detectability predictions in VHE are complex, due to variability and the unknown intrinsic spectral shape. Two methods have been proposed to tackle this:
  – Deep blazar observations.
  – Extrapolations from the HE regime.
- We created a tool to test the consistency between extrapolations from HE data with real blazar observations in the VHE regime: `ext2TeV`
- We tested the tool with 43 VHE AGNs recorded in different states within two VHE catalogs: *GammaCAT* and *VTSCat*.
- We performed a simple statistical analysis to test the validity of several extrapolation schemes for different AGN spectral classes.

References

[1] `http://tevcat.uchicago.edu/`. 2021-05.
[2] H. Abdalla et al. *JCAP*, 2021(2):048, 2021.
[3] `https://github.com/gammapy/gamma-cat`. 2021-05.
[4] W. Benbow et al. `https://zenodo.org/record/4964083`, 2021.
[5] A. Domínguez et al. MNRAS, 410(4):2556–2578, 2011.