Persistent γ-ray emission of the blazar PKS 1510–089 in its low state: Fermi-LAT data analysis and theoretical modelling

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ABSTRACT
Blazars may accelerate protons and/or nuclei as well as electrons. The hadronic component of accelerated particles in blazars may constitute the bulk of their high-energy budget; nevertheless, this component is elusive due to a high value of the energy threshold of proton interaction with photon fields inside the source. However, broad line regions (BLRs) of some flat spectrum radio quasars (FSRQs) may contain a sufficient amount of matter to render primary protons “visible” in γ rays via hadronuclear interactions. In the present paper we study the persistent γ-ray emission of the FSRQ PKS 1510–089 in its low state utilizing the publicly-available Fermi-LAT data, as well as using the spectrum measured with the MAGIC imaging atmospheric Cherenkov telescopes. We find an indication for an excess of γ rays at the energy range $\gtrsim 10$ GeV with respect to a simple baseline log-parabolic intrinsic spectral model. The statistical significance of the excess is $\approx 5.5\sigma$, but it drops to $\approx 2.7\sigma$ after the account of the systematic uncertainty of the MAGIC measurements. This excess could be explained in a scenario invoking hadronuclear interactions of primary protons on the BLR material with the subsequent development of electromagnetic cascades in photon fields. We present a Monte Carlo calculation of the spectrum of this cascade component, taking as input the BLR photon field spectrum calculated with the Cloudy code. To our knowledge, this is the first calculation of electromagnetic cascade spectrum inside a blazar based on a direct calculation of the photon field spectrum with a spectral synthesis code.

Key words: galaxies: active – galaxies: nuclei – gamma-rays: galaxies – radiation mechanisms: non-thermal – methods: numerical methods: data analysis – quasars: individual: PKS 1510–089

1 INTRODUCTION
The extragalactic high-energy (HE, $E > 100$ MeV) γ-ray sky is dominated by blazars (Abdollahi et al. 2020; Wakely & Horan 2008) — active galactic nuclei with relativistic jets pointing towards the observer. A large fraction1 of non-thermal power radiated by blazars could be attributed to leptonic processes inside the so-called “blobs” — clouds of magnetized plasma propagating along the jets. Besides electrons, protons and/or nuclei2 could also have been accelerated in blobs/jets of blazars. In 2018, the IceCube collaboration reported on the evidence for astrophysical neutrinos from the blazar TXS 0506+056 (Aartsen et al. 2018a,b), thus indicating that hadronic processes are indeed in operation in blazars. Remarkably, TXS 0506+056 was classified by Padovani et al. (2019) as a flat spectrum radio quasar (FSRQ). FSRQs are believed to contain the broad line region (BLR) matter in the form of clouds or wind. High-energy protons accelerated in blobs or jets of FSRQs

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1 in some models — almost an entirety
2 in what follows we consider the case of the primary protons
can sometimes interact with this matter, resulting in observable fluxes of γ rays and neutrinos (e.g. Dar & Laor (1997); Bednarek & Protheroe (1997); Beall & Bednarek (1999); Araudo et al. (2010); del Palacio et al. (2019)).

Accelerated protons are likely to be responsible for the bulk of the high-energy budget in blazars. Nevertheless, in the absence of intervening matter, the protons with the energy below 1–10 PeV may be almost “sterile”, i.e. in many FSRQs such protons may lose only a small fraction of their energy before escaping from the jet. This conclusion follows from the fact that FSRQs were detected in the very-high-energy domain (VHE, $E > 100$ GeV) with imaging atmospheric Cherenkov telescopes (IACTs) (e.g. (Albert et al. 2008; Aleksić et al. 2011; H.E.S.S. Collaboration et al. 2013)). These observations imply a reasonably low intrinsic $\gamma \gamma \rightarrow e^+e^−$ pair production (PP) optical depth $\tau_{\gamma\gamma} < 2 − 3$ below 100 GeV. Indeed, the effective $\gamma$-ray PP energy threshold is $E_{\text{thr,}\gamma\gamma} = E_{\gamma} (E_{\gamma} / 1$ eV)$^{-1}$, where $E_{\gamma}$ [eV] is the characteristic energy of the intrinsic photon field, and $E_{\gamma} \sim 1$ TeV. Therefore, $E_{\gamma} < 10$ eV is implied by the VHE observations. On the other hand, the effective proton energy threshold for the photopion process is $\sim 4$ PeV$\times (E_{\gamma}/10$ eV)$^{-1}$ (e.g. Berezhinskii et al. (2006))

Thus, in order to study the TeV-PeV population of protons inside blazars, it is desirable to search for a signature of hadronuclear (proton-proton, pp) interactions in these sources. The importance of such a search is still more emphasized by the fact that a significant part of the useful astrophysical neutrino signal of IceCube corresponds to the neutrino energy range of 10–300 TeV, translating to the proton energy range of 100 TeV to 3 PeV (e.g. Kelner et al. (2006); Kelner & Aharonian (2008)).

Such a signature of pp interactions could be present in γ-ray spectra of some FSRQs in the form of a distinct component at very high energies. Primary protons can interact on material embedded into the broad line region; for instance, pp collisions can take place at the distance from the central black hole of $0.8 − 0.9 R_{\text{BLR}}$, where $R_{\text{BLR}}$ is the characteristic radius of the BLR. In this scenario, the “residual” optical depth for γ rays exiting the BLR region is $5 − 10$ times smaller than the “full” optical depth for γ rays produced near the center of the BLR. Therefore, a part of sub-TeV or even TeV γ rays produced near the edge of the BLR could escape the BLR; another part of such γ rays could be re-generated in electromagnetic cascades developing in the BLR photon field. This scenario for the 2014–2015 neutrino emission episode of TXS 0506+056 was considered by Dzhatdoev (2019)

We argue that one of the best candidates for the search of the aforementioned spectral signature is the blazar PKS 1510–089. PKS 1510–089 (cosmological redshift $z = 0.361$) was classified as a FSRQ (Tanner et al. 1996). VHE γ-ray emission of this source was discovered with the H.E.S.S. telescopes (H.E.S.S. Collaboration et al. 2013). Persistent VHE γ-ray emission of PKS 1510–089 over the years from 2012 to 2017 was detected with the MAGIC telescopes (MAGIC Collaboration et al. 2018). Such emission could come directly from the jet, while flares could be attributed to blobs. If the jet of PKS 1510–089 accelerates protons up to the energy of at least several TeV, we expect the existence of a sub-TeV γ-ray component in the observable spectrum. If the maximal energy of these protons is in excess of 100 TeV, neutrino(s) from PKS 1510–089 could be detected with IceCube or similar neutrino telescopes. In the present paper we study the persistent HE and VHE γ-ray emission of PKS 1510–089 in its low state. In Section 2 we describe the Fermi-LAT (Atwood et al. 2009) space γ-ray telescope data analysis for PKS 1510–089 performed by us. Using combined Fermi-LAT and MAGIC data, in Section 3 we report on a tentative $\gtrsim 10$ GeV excess of γ rays with respect to a baseline model. This excess could be attributed to the hadronuclear component discussed above. In Section 4 we present the two-component model. In Section 5 we discuss the results and put these results into the context of contemporary blazar studies. Finally, we conclude in Section 6.

2 FERMI-LAT DATA ANALYSIS

2.1 Data selection and analysis setup

The data were taken from the Fermi-LAT data server7 over the time period from the 4th of August, 2008 to the 6th of April, 2020. The region of interest (ROI) is a square with the width of $10^\circ$ and the center at the position of PKS 1510–089 (4FGL J1512.8-0906 in the 4th Fermi-LAT source catalog 4FGL (Abdollahi et al. 2020)). We consider the energy range from 100 MeV to 300 GeV, four logarithmic bins per energy decade. For our analysis, we select events of the P8R3 SOURCE class. Using the fermipy package (Wood et al. 2017) and assuming the P8R3_SOURCE_V2 instrument response function set8, we perform a binned likelihood off-plane point source analysis following the standard recommendations for this type of analysis9.

We constructed a model of the observed γ-ray emission consisting of the following components: 1) PKS 1510–089, the source of interest; 2) all other 4FGL sources within a $15^\circ$-circle centered at the position of PKS 1510–089; 3) galactic and isotropic background γ-ray emissions, represented by the gll_iem_v07 and iso_P8R3_SOURCE_V2_v1 models, respectively10. We modelled the spectrum of PKS 1510–089 with the PowerLaw11 function allowing its two parameters (photon flux and spectral index) to vary freely during the model optimization. Photon fluxes of diffuse γ rays and 4FGL sources within $3^\circ$ from the ROI center were also left free, while other model parameters, including 4FGL sources' spectral parameters and photon fluxes from sources outside of the radius of $3^\circ$ from the ROI center, were fixed at their catalog values.

2.2 PKS 1510–089 low state identification

In this paper we focus on the persistent γ-ray emission from PKS 1510–089 in its “low” state. Low state, as opposed to high (ac-

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3 at least in the framework of geometrically simple, one-zone emission models
4 the energy threshold of the Bethe-Heitler process is somewhat lower; however, neutrinos are not produced in this process
5 below 10 TeV a tremendous atmospheric neutrino background is present, while above 300 TeV the number of expected neutrinos in IceCube is relatively small for most of the conceivable discrete sources
6 in fact, it is a modified scenario of Dar & Laor (1997)

7 https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi
8 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html
9 https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html
10 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
11 https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/xml_model_defs.html
two of these items were identified by us as belonging to the high state (these are shown in red in the lower panel of Fig. 2).

2.3 Spectral energy distribution

For the spectral analysis of PKS 1510–089 we used the low state data for the whole Fermi-LAT observation period. We modified our ROI model altering the spectrum shape of the source of interest to that of the log-parabolic function. During the optimization procedure both normalization and spectral shape of PKS 1510–089 were left free. The SED obtained with GTAnalysis.sed fermipy method is shown in Fig. 3 as blue circles with statistical error bars.

The SED of PKS 1510–089 obtained by the MAGIC Collaboration (MAGIC Collaboration et al. 2018, Fig. 7) is also presented in Fig. 3. We note that, taking into consideration both the systematic and statistical uncertainties of the ground-based telescope measurements, Fermi-LAT and MAGIC SEDs are in good agreement.

3 THE HIGH-ENERGY EXCESS OF γ RAYS ABOVE 10 GeV

We fit the measured γ-ray spectrum of PKS 1510–089 as follows. The intrinsic spectrum (i.e. the spectrum before the intergalactic propagation effects are taken into account) is described with a log-parabolic function:

\[
\frac{dN}{dE_{\gamma}} = K_0 \left( \frac{E_{\gamma}}{E_{0}} \right)^{-(\alpha + \beta \ln(E_{\gamma}/E_{0}))},
\]

where \(K_0\) is the normalization parameter, \(E_{0}\) — the “reference energy”, \(\alpha\) — the power-law index, \(\beta\) — the curvature parameter. Furthermore, we account for the effects of \(\gamma\gamma\) pair production on the extragalactic background light (EBL) (Nikishov 1962; Gould & Schrédé 1967) and adiabatic losses (redshift). We assume the EBL model of Gilmore et al. (2012). The fitting of the observed Fermi-LAT and MAGIC SEDs was performed considering \(K_0\), \(\alpha\), and \(\beta\) as independent parameters. The value of \(E_{0}\) was fixed at 10 GeV.

We obtained fits for three different MAGIC datasets, namely, baseline measurements (red filled squares in Fig. 3), lower (purple hollow squares), and upper (brown hollow squares) boundary measurements, thus taking into consideration the MAGIC systematic uncertainty. For the first fit we obtained the following values of parameters: \(K_0 = 2.84 \times 10^{-16} \text{ eV}^{-1}\text{cm}^{-2}\text{s}^{-1}\), \(\alpha = 2.64\), \(\beta = 0.064\). The SED corresponding to this model is denoted in Fig. 3 as model 0. The other two fits obtained almost coincide with the first one and are not shown.

Quality of the obtained fit is rather poor: \(\chi^2/\text{n.d.o.f.} = 4.47\) for the baseline MAGIC measurements, \(\chi^2/\text{n.d.o.f.} = 2.16\) for the lower boundary of MAGIC measurements, and \(\chi^2/\text{n.d.o.f.} = 8.25\) for the upper boundary of MAGIC measurements, where n.d.o.f. = 18−3−1 = 14 is the number of degrees of freedom, \(\chi^2\) is the sum of squared differences between model values at the central energy of every observational bin and observed values of the SED divided by the corresponding statistical error. The empirical significance of the model 0 rejection is \(\approx 5.5\sigma\) for the baseline MAGIC measurements, \(\approx 2.7\sigma\) for the lower boundary of MAGIC measurements, and \(> 8\sigma\) for the upper boundary of MAGIC measurements.

The high-energy part of the SED (\(\gtrsim 10\) GeV) reveals some excess of γ rays. In the next Section we consider a particular model

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Figure 1. Empirical PDF of photon fluxes. Black curve represents the Gaussian fit for the PDF, red line represents its 3σ quantile that was chosen as a low state photon flux threshold.

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12 more precisely, the dependence of the empirical PDF bin content on the value of the photon flux corresponding to the center of the bin

13 https://raw.githubusercontent.com/fermi-lat/fermitools-fhelp/master/gltsum.txt
of this excess invoking hadronuclear interactions of primary protons with subsequent development of electromagnetic cascades in photon field.

4 HADRONNUCLEAR INTERPRETATION OF THE \( \gtrsim 10 \) GEV EXCESS IN THE LOW STATE OF PKS 1510–089

4.1 Geometry of the flat-spectrum radio quasar PKS 1510–089

A simplified scheme of the geometry of the blazar PKS 1510–089 is shown in Fig. 4. The source is powered by a central engine represented by a supermassive black hole and an accretion disk. The BLR contains some matter that is shown in Fig. 4 as pale orange circles. This material represents a target for hadronuclear interactions of primary protons. In addition, the BLR material reprocesses radiation from the accretion disk forming the BLR photon field. The outer boundary of the BLR has the radius \( R_{BLR} \).

Primary protons are accelerated up to the maximal energy of \( \sim 1 \) PeV in the jet of the blazar; \( pp \) interactions result in the production of \( \gamma \) rays at the distance \( \leq R_{BLR} \) from the supermassive black hole. For simplicity, we assume that the proton interaction site is a compact region, even though in reality it may well have significant extension amounting up to 20-30 \% of the BLR radius. Moreover, electrons and positrons\(^{14} \) with energies similar to those of the \( \gamma \) rays are produced. In what follows we neglect these electrons and positrons. The effect of this assumption is discussed in Section 5.

Some \( \gamma \) rays escape the production region into the “residual” BLR photon field occupying the distance range from \( x_p \) to \( R_{BLR} \); these \( \gamma \) rays may initiate electromagnetic cascades\(^{15} \). Observable \( \gamma \) rays from electromagnetic cascades may explain the high-energy excess reported in the previous Section. Finally, the low-energy (log-parabolic) component may be produced at the edge of the BLR or outside of the BLR, as assumed in some contemporary FSRQ \( \gamma \)-ray emission models (see e.g. Meyer et al. (2019)).

4.2 The spectrum of the BLR photon field

The spectrum of the photon field inside the broad line region was calculated with the Cloudy code\(^{16} \), version c17.00 (Ferland et al. 2017). The following values of input parameters were assumed: the bolometric luminosity of the accretion disk \( L_D = 10^{46} \) erg/s.

\(^{14} \) in what follows electrons and positrons are collectively called “electrons” for simplicity

\(^{15} \) hadronuclear \( \gamma \) rays are “primary” particles for electromagnetic cascades, as noted in Fig. 4, but they are secondary particles with respect to the protons producing them

\(^{16} \) www.nublado.org
Figure 3. The Fermi-LAT (our analysis, blue circles) and MAGIC (squares, data taken from (MAGIC Collaboration et al. 2018, Fig. 7)) low-state SEDs of PKS 1510–089. Filled squares represent baseline MAGIC measurements, hollow squares denote the MAGIC systematic uncertainty in energy and SED measurements. Solid curve represents the model 0 with extragalactic absorption taken into account.

Figure 4. A sketch of the geometry of the FSRQ PKS 1510–089 adopted in our model (not to scale). See text for details.

the BLR radius $R_{BLR} = 0.036$ pc, the BLR material covering factor $f = 0.1$, the hydrogen density $n_H = 10^{10}$ cm$^{-3}$, and the column density $N_e = 10^{23}$ cm$^{-2}$. The spectrum of the accretion disk was assumed to follow the model “AGN” implemented in Cloudy with the characteristic temperature parameter amounting to $10^5$ K. Other parameters were set to their default values.

The BLR radius for PKS 1510–089 was measured by Rakshit (2020) with the reverberation mapping technique. The value of $L_D$ assumed by us is between the estimates of Abdo et al. (2010) ($3 \times 10^{45}$ erg/s) and Rakshit (2020) ($2.15 \times 10^{46}$ erg/s). The values of other parameters are typical for FSRQ studies (see, e.g., Tavecchio & Ghisellini 2008).

After running the Cloudy simulation, we obtained the spectral density for the photon field reflected into the BLR $n(E)$ (in units
of eV$^{-1}$ cm$^{-3}$), which was used as a background photon field for high-energy γ rays. For simplicity, we assume that this photon field is homogeneous and isotropic. Detailed calculations of Abolmasov & Poutanen (2016) show that this is indeed a reasonable first-order approximation.

4.3 Two-component γ-ray emission model for the low state of PKS 1510–089

Here we describe our calculation of the observable γ-ray approximation.

\[
\frac{dN_{\gamma}}{dE_{\gamma}} = K_{\gamma} \left( \frac{E_{\gamma}}{E_{0}} \right)^{-\gamma_{\gamma}}
\]

where proton energy $E_{p}$ lies in the range between $E_{p_{\text{min}}} = 10^{15.50}$ eV and $E_{p_{\text{max}}} = 10^{17.77}$ eV; $\gamma_{\gamma} = 2.0$ and $E_{0} = 10^{10}$ eV.

In what follows we use approximations of Kelner et al. (2006) for the proton-proton inelastic cross section $\sigma_{pp}(E_{p})$ and the secondary γ-ray spectrum $dN_{\gamma}/dE_{\gamma}$. For the matter column density $N_{\text{BLR}} = 10^{23}$ cm$^{-2}$, the optical depth for $pp$ interactions is

\[
\tau_{pp}(E_{p}) = N_{\text{BLR}} \sigma_{pp}(E_{p}).
\]

The spectrum of interacting primary protons, which produce secondary γ rays, is calculated as

\[
\left( \frac{dN_{\gamma}}{dE_{\gamma}} \right)_{\text{sec}} = \frac{dN_{\gamma}}{dE_{\gamma}} \left( 1 - \exp \left[ -\tau_{pp}(E_{p}) \right] \right).
\]

Furthermore, we assume that the γ-ray production site is situated at a fixed distance from the central engine $x_{p} = 0.9R_{\text{BLR}}$. The γ-ray production site for the low energy component with the logarithmic spectrum is denoted as $x_{\gamma}$. The precise value of $x_{\gamma}$ is uncertain. Fig. 4 presents the option of $x_{\gamma} \lesssim R_{\text{BLR}}$; however, the option of $x_{\gamma} \gtrsim R_{\text{BLR}}$ is also viable. In Section 3 we conservatively assumed the latter option because it yields the lowest value of the statistical significance of the high-energy excess.

Most of γ rays produced in hadronuclear interactions of the primary protons with the BLR material escape into the BLR photon field, propagate further along the jet (see blue waves in Fig. 4), and initiate electromagnetic cascades on the BLR photon field. A small part of γ rays produce electron-positron pairs on the BLR material; in what follows, we do not account these interactions. The development of electromagnetic cascades proceeds as follows. Most of the hadronuclear γ rays produce electron-positron pairs on the BLR photon field with the energy density distribution $n(E)^{18}$ Electrons produced in the PP process are shown as blue dotted lines in Fig. 4. These electrons are, in turn, subject to the inverse Compton (IC) process (see, e.g., Blumenthal & Gould 1970) resulting in the transfer of energy from them to the photons of the BLR photon field, thus producing the next-generation γ rays of the cascade (subsequent blue waves in Fig. 4). The cascade may comprise one or more generations. To calculate the spectrum of electromagnetic cascades we developed a Monte Carlo code, for the most part of this work following the prescriptions of Kachelriß et al. (2012) for the total and differential cross sections of the PP and IC processes. We neglect

the synchrotron energy losses for cascade electrons. We note that the difference of our algorithm from the one presented by Kachelriß et al. (2012) is relatively small.

Using this code, we calculated the spectra of observable γ rays for $N_{0} = 30000$ cascades with the primary γ-ray energy distributed according to the power-law spectrum with the spectral index $-1$ and energies varying in the range from $10^{16}$ eV to $5 \times 10^{18}$ eV. The energies of all primary γ rays and cascade γ rays which reach the edge of the BLR (when $x = R_{\text{BLR}}$) and become observable are recorded. For all observable cascade γ rays information about the energy of the primary γ ray, which initiated the development of a particular electromagnetic cascade, is collected. This allows us to reweigh the resulting spectrum of observable γ rays according to the primary spectrum $dN_{\gamma}/dE_{\gamma}$ of γ rays produced in $pp$ interactions.

The low-energy component has three free parameters ($K_{\gamma}, \alpha, \beta$). Concerning the high-energy component, the values of $(E_{p_{\text{min}}, p_{\text{max}}}, \gamma_{\gamma})$ were fixed above. The only free parameter remaining is the normalization of the proton spectrum $K_{p}$. We performed the fitting of the two-component model to the observational data and obtained the following best-fit values of the parameters: $K_{\gamma} = 2.27 \times 10^{-19}$ eV$^{-1}$cm$^{-2}$s$^{-1}$, $\alpha = 2.79$, $\beta = 0.088$, $K_{p} = 1.96 \times 10^{-16}$ eV$^{-1}$cm$^{-2}$s$^{-1}$.

The observable γ-ray component from cascades is shown in Fig. 5 as a dashed red curve. In this figure we present the low-energy component (dashed black curve) and the total observable γ-ray SED (solid brown curve) as well. The latter SED is the sum of the two former components. For all three presented SEDs the effect of the extragalactic absorption of γ rays was taken into account assuming the EBL model of Gilmore et al. (2012). Taking into consideration the systematic uncertainties of the MAGIC measurements, we conclude that the two-component model describes observational data reasonably well over the whole energy range available.

5 DISCUSSION

In this paper, we have found an indication for an excess of γ rays at the energy $E \gtrsim 10$ GeV for the low state of PKS 1510–089. In the previous Section we have described a specific model of this excess involving hadronuclear interactions of multi-TeV protons with the subsequent development of electromagnetic cascades on the BLR photon field. This model is supported with an observation of a particular case of jet-cloud interactions in radio galaxy 3C 84 that was recently reported by Kino et al. (2021).

Most of works on blazar γ-ray emission ignore electromagnetic cascades. This phenomenon was occasionally studied in context of emission models of various types of active galactic nuclei (Blandford & Levinson 1995; Neronov & Aharonian 2007; Aharonian et al. 2008; Roustazadeh & Böttcher 2010; Wendel et al. 2021a,b). However, to the best of our knowledge, the present work is the first paper where the simulation of electromagnetic cascades in the BLR photon field is based on a direct calculation of the photon field spectrum with a spectral synthesis code such as Cloudy.

We note that our model could be further elaborated in a number of ways discussed below.

(i) It was assumed that the radius of the proton interaction site is much smaller than the BLR radius. This simplifying assumption could be reconsidered in the future, including $x_{p}$ as another free parameter of the model and allowing for an extended proton in-

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Figure 5. Spectral energy distribution of PKS 1510–089. Observational data points are the same as in Fig. 3. Solid brown curve denotes the two-component model SED. Separate components of the model are also shown as dashed curves (see plot legend). Dot-dashed purple curve represents the SED of primary (for electromagnetic cascades) γ-rays produced in proton-proton (pp) collisions in the source frame; this curve peaks at the energy of ~10^{13} eV.

given that blazars are believed to be strongly beamed γ-ray sources

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20 however, Zhou et al. (2021) have questioned the association of IceCube neutrinos with radio-bright AGN
cess at energies $E \gtrsim 10$ GeV is common for other FSRQs in their low states.

6 CONCLUSIONS

In this work we studied persistent $\gamma$-ray emission of the blazar PKS 1510–089. We performed a Fermi-LAT data analysis identifying the low-state periods of PKS 1510–089 $\gamma$-ray emission and combining Fermi-LAT and MAGIC observations to obtain the SED of the blazar in the energy range from 100 MeV to $\approx 500$ GeV. We found an indication of the $\gamma$-ray excess at energies $E \gtrsim 10$ GeV (the conservative estimate of the statistical significance gives $\approx 2.7\sigma$). The observed SED could be reasonably well fitted in the framework of the two-component model with a lower-energy component well described with the log-parabolic intrinsic spectrum, and the higher-energy component resulting from $pp$ collisions of 30–600 TeV protons interacting with the BLR material followed by the development of electromagnetic cascades in the BLR photon field.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Aartsen M. G., Ackermann M., Adams J., Aguilar J. A., Ahlers M., et al. 2018a, Science, p. eaat1378
Aartsen M. G., Ackermann M., Adams J., Aguilar J. A., Ahlers M., et al. 2018b, Science, p. eaat2890
Abdo A. A., Ackermann M., Aguado I., Ajello M., Allafort A., et al. 2010, The Astrophysical Journal, 721, 1425
Abdollahi S., Acero F., Ackermann M., Ajello M., Atwood W. B., et al. 2020, The Astrophysical Journal Supplement Series, 247, 33
Abolmasov P., Poutanen J., 2016, Monthly Notices of the Royal Astronomical Society, 464, 152
Aharonian F. A., Khangulyan D., Costamante L., 2008, Monthly Notices of the Royal Astronomical Society, 387, 1206
Albert J., Aliu E., Anderhub H., Antonelli L. A., Antoranz P., et al. 2008, Science, 320, 1752
Aleksić J., Antonelli L. A., Antoranz P., Backes M., Barrio J. A., et al. 2011, ApJ, 730, L8
Araudo A. T., Bosch-Ramon V., Romero G. E., 2010, Astronomy & Astrophysics, 522, A97
Atwood W. B., Abdo A. A., Ackermann M., Althouse W., Anderson B., et al. 2009, ApJ, 697, 1071
Beall J. H., Bednarek W., 1999, The Astrophysical Journal, 510, 188
Bednarek W., Protheroe R. J., 1997, Monthly Notices of the Royal Astronomical Society, 287, L9
Berezinsky V., Kalashev O., 2016, Phys. Rev. D, 94
Berezinsky V., Garzio A., Grigorieva S., 2006, Physical Review D, 74, 043005
Blandford R. D., Levinson A., 1995, ApJ, 441, 79
Blumenthal G. R., Gould R. J., 1970, Reviews of Modern Physics, 42, 237
Dar A., Laor A., 1997, ApJ, 478, L5
Dzhatdoev T. A., 2019, A mixed origin of neutrinos from TXS 0506+056, Talk at the TeVPA-2019 conference, https://indico.cern.ch/event/624338/timetable/?print=1\&view=standard#136-a-mixed-origin-of-neutrino
Ferland G. J., et al., 2017, Revista Mexicana de Astronomia y Astrofisica, 53, 385
Gilmore R. C., Somerville R. S., Primack J. R., Domínguez A., 2012, Monthly Notices of the Royal Astronomical Society, 422, 3189
Gould R. J., Schréder G. P., 1967, Phys. Rev., 155, 1408
H.E.S.S. Collaboration Abramowski A., Acero F., Aharonian F., Akhperjanian A. G., Anton G., et al. 2013, Astronomy & Astrophysics, 554, A107
Kachelrieß M., Ostapchenko S., Tomás R., 2012, Computer Physics Communications, 183, 1036
Kelner S. R., Aharonian F. A., 2008, Physical Review D, 78
Kelner S. R., Aharonian F. A., Bugayov V. V., 2006, Physical Review D, 74
Kino M., et al., 2021, ApJ, 920, L24
MAGIC Collaboration Acciari V. A., Ansoldi S., Antonelli L. A., Engels A. A., Arcaro C., Baack D., et al. 2018, Astronomy & Astrophysics, 619, A159
Massaro E., Perri M., Giommi P., Nesci R., 2003, A&A, 413, 489
Meyer M., Scargle J. D., Blandford R. D., 2019, The Astrophysical Journal, 877, 39
Neronov A., Aharonian F. A., 2007, The Astrophysical Journal, 671, 85
Nikishov A. I., 1962, Sov. Phys. JETP, 14, 393
Padovani P., Oikonomou F., Petropoulou M., Giommi P., Resconi E., 2019, MNRAS Lett., 484, L104
Plavin A., Kovařek Y., Kovařek Y., Troitsky S., 2020, ApJ, 894, 101
Plavin A. V., Kovařek Y., Kovařek Y., Troitsky S. V., 2021, ApJ, 908, 157
Potter W. J., Cotter G., 2012, MNRAS, 423, 756
Rakshit S., 2020, Astronomy & Astrophysics, 642, A59
Roustatzadeh P., Bottcher M., 2010, The Astrophysical Journal, 717, 468
Roy A., Patel S. R., Sarkar A., Chatterjee A., Chattini V. R., 2021, MNRAS, 504, 1103
Tanner A. M., Bechtold J., Walker C. E., Black J. H., Cutri R. M., 1996, AJ, 112, 62
Tavecchio F., Ghisellini G., 2008, Monthly Notices of the Royal Astronomical Society, 386, 945
Tramacere A., Massaro E., Taylor A. M., 2011, ApJ, 739, 66
Wakely S. P., Horan D., 2008, in International Cosmic Ray Conference. pp 1341–1344, http://tevatron2.uchicago.edu/
Wendel C., González J. B.,Paneque D., Mannheim K., 2021a, A&A, 646, A115
Wendel C., Shukla A., Mannheim K., 2021b, ApJ, 917, 32
Wood M., Caputo R., Charles E., Di Mauro M., Magill J., Perkins J. S., Fermi-LAT Collaboration 2017, in 35th International Cosmic Ray Conference (ICRC2017). p. 824 (arXiv:1707.09551)
Zhou B., Kamionkowski M., Feng Liang Y., 2021, Phys. Rev. D, 103
del Palacio S., Bosch-Ramon V., Romero G. E., 2019, Astronomy & Astrophysics, 623, A101

APPENDIX A: LOW STATE IDENTIFICATION USING 2D CLASSIFICATION WITH SPECTRAL INDEX AND PHOTON FLUX

In addition to the low-state identification procedure described in Section 2.2 we made an attempt to separate low- and high-state $\gamma$-ray emissions of PKS 1510–089 using two-dimensional analysis with spectral index and photon flux as independent variables. Fig. A1 shows the resulting scatter plot with mean and median points, as well as 1$\sigma$, 2$\sigma$, and 3$\sigma$ bounding ellipses. For comparison, the final photon flux threshold from Fig. 1 is plotted as horizontal red line.
Persistent γ-ray emission of PKS 1510–089

Figure A1. Scatter plot of independent spectral parameters. Each dot represents values of the spectral index and the photon flux corresponding to two days of observations.

It is clear that, although a slight positive correlation is present between the spectral index and the photon flux, it should not significantly affect the state separation procedure. Moreover, a strict lower bound on photon flux makes it impossible to use the bivariate normal distribution approximation (which is also clear from the displaced $n\sigma$ ellipses) and demands a more sophisticated analytical or numerical solution. We therefore conclude that the empirical PDF-based photon flux procedure described in Section 2.2 is sufficient for the low-state identification.

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