Blazar halos as probe for extragalactic magnetic fields and maximal acceleration energy

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***Abstract*. High energy photons from blazars interact within tens of kpc with the extragalactic photon background, initiating electromagnetic pair cascades. The charged component of such cascades is deflected by extragalactic magnetic fields (EGMF), leading to halos even around initially point-like sources. We calculate the intensity profile of the resulting secondary high-energy photons for different assumptions on the initial source spectrum and the strength of the EGMF, employing also fields found earlier in a constrained simulation of structure formation including MHD processes. We find that the observation of halos around blazars like Mrk 180 probes an interesting range of EGMF strengths. Blazar halos test also if the photon energy spectrum at the source extends beyond $\sim 100\,$TeV and how anisotropic this high energy component is emitted.**

***Keywords*: Cosmic rays; γ rays; active galactic nuclei.**

I. INTRODUCTION

Observations of photons with energies up to tens of TeV, mainly by imaging air Cherenkov telescopes (IACT), have opened in the last decade a new window on the non-thermal side of the Universe [1]. One of the main aims of these observations is the identification of the sources of cosmic rays and their acceleration mechanism. Observations of very high energy photons can however provide information on many more areas of astrophysics, as e.g. the amount of extragalactic background light (EBL) and the strength of extragalactic magnetic fields (EGMF).

The tight relationship between the EBL, the strength of EGMFs and the horizon of high energy photons is well-known: Photons with energy above the pair creation threshold, $E_{\rm th} \sim 30\,$TeV for $E \sim 10^{-2}\,$eV as characteristic energy of the background photons, can interact with background photons, initiating electromagnetic pair cascades [2]. The charged component of such cascades is in turn deflected by magnetic fields, first by fields in the cluster surrounding the source [3] and then by EGMFs [4]. If the EGMF is not extremely week, $B \lesssim 10^{-16}\,$G, secondary photons are deflected outside a point-like source and thus the observed point-like photon flux $I(E)$ consists only of the surviving primary photons, $I(E) = \exp[-\tau_{\gamma\gamma}(E)]I_0$, with $\tau_{\gamma\gamma}$ as the depth for pair production. If the EGMF exceeds $10^{-10}\,$G in a large volume fraction, the halo becomes too large and its intensity therefore too small for a detection. In the intermediate range, $(10^{-16}$–$10^{-10})\,$G, the deflections and thus the halo extension may be sufficiently small that an observation by current or next generation IACTs may be feasible [4].

We focus in this work on the effect of EGMFs on electromagnetic cascades, providing detailed predictions for the expected intensity $I(E,\theta)$ of the halo produced by cascades as function of the observed energy E and the angular distance θ to the source. Since the EGMF is highly structured and the Milky Way is contained in the supergalactic plane, the magnetic field along the line-of-sight to different blazars, and thus also their halos, will vary significantly, even if they would be at the same distance and would have the same source energy spectrum. It is therefore crucial to use an EGMF model that describes at least qualitative correctly the location of voids and filaments. Since deflections close to the observer are most important, it is sufficient to account for the EGMF structure of the local universe. For our predictions of the expected halo intensity $I(E,\theta)$ around selected blazars we use therefore EGMF models calculated in Ref. [5] that are based on a constrained simulation of the large-scale structure within $\approx 115\,$Mpc.

The results here presented are based on analysis carried out in Ref. [6]. They confirm the estimate of Ref. [4] that blazar halos are detectable, if EGMFs are as weak as found in the simulations of Ref. [5]. Thus blazar halos may provide valuable information about the strength of EGMFs in a range where other tools like Faraday rotation measurements can give only upper limits. Moreover, our detailed predictions for the expected intensity $I(E,\theta)$ of the halo produced by the electromagnetic cascade allow one to disentangle the contributions from secondaries generated close to the source, as suggested in Ref. [3], and during propagation in the EGMF. The intensity of the halo is also sensitive to the total luminosity of the source above $\sim 100\,$TeV and to the opening angle θ of the cone in which most of this high energy radiation is emitted.

We find that the measured energy spectrum of most blazars detected with IACTs may be described by a broken power-law that is steeper in the measured energy range (100 GeV–few TeV) than usually assumed, if one adds a softer high energy component. This additional high-energy component is absent both in Synchrotron Self-Compton SSC and Inverse Compton models for blazars [7], but may be caused by hadrons [8], [9]. In most hadronic models, e.g. acceleration close to the core in electromagnetic fields or in hot spots, the bulk of radiation, although emitted anisotropically, extends over a cone with opening angles $\alpha_{\rm jet} \gtrsim 10^\circ$. For such conditions, we found that the halo is not strongly suppressed. Thus the observation of blazar halos would be an indication for an extension of the source photon spectrum beyond 100 TeV that is not strongly beamed and thus also evidence for the acceleration of hadrons in blazars.

II. HALO PREDICTIONS FOR SELECTED BLAZARS

In this section we perform a realistic study of the blazar halos for four of the nearest blazars, Mrk 180, Mrk 501, 1ES 1959+650 and 1ES 2344+514. The low luminosity of Mrk 421 above the pair creation threshold makes it an unfavorable candidate for the search of blazar halo [6].

We study the propagation of the electromagnetic (e/m) cascade in the extragalactic space using a one-dimensional MC method as described in Ref. [6]. We used the EGMF along the line-of-sight towards the four blazars that results from a constrained realization of the local universe (see Ref. [5] and references therein). For this work we used the magnetic field configuration obtained from two realizations (MHDy and MHDz) starting from different initial seed fields (for more details see Ref. [5]) having higher (MHDy) and lower (MHDz) initial values for the magnetic seed field. We will first present results for the model MHDz that generally predicts stronger localisation of magnetic fields in cluster and filaments and thus smaller deflections than model MHDy. A comparison of the field perpendicular to the line-of-sight towards Mrk 180 is shown for the two simulations in the left panel of Fig. 3.

We show our results in Fig. 1 for Mrk 180 (top) and Mrk 501 (bottom) and in Fig. 2 for 1ES 1959+650 (top) and 1ES 2344+514 (bottom). The left panels represent the integral intensity $I(> E_0, \theta)$ as function of the angular distance θ to the source. The right panels show the differential energy spectra for three angular bins: The solid lines include both the point-like and the halo component within $\theta < \theta_0 = 0.03^\circ$ (from now on called 'point-like'), while the dotted lines denote the mean intensity between $\theta_0 < \theta < 2\theta_0$ ('halo 1') and the dashed lines denote the intensity at $\theta = 0.6^\circ$ ('halo 2'). The differential energy spectrum of each source is calculated for two different injection spectra: In the first case, we assume that the observed spectrum extends with the same slope γ_1 up to $E_{\max} = 10^{17}$ eV. In the second case, we add a new, harder component with $\gamma_2 < \gamma_1$ that may be generated in particular by hadrons. Thus, we use as injection spectrum a broken power-law, adjusting the parameters like the break energy E_b such that we reproduce the observed spectral shape while optimizing the halo flux.

A characteristic feature of the second case is a small bump between the break energy and the exponential cut-off at $E_{\rm th}$ introduced by the EBL interactions. Clearly, blazars which show a cutoff at energies below $E_{\rm EBL}$ can have only a minor additional hard component compared to blazars which show either no cutoff or even a turn up. As one can see from the Figures, for the "broken" power-law case we get very pronounced halos in the TeV range for Mrk 180 and 1ES 2344+514, with the halo intensity being comparable to the one of the point-like component.

In the right panel of Fig. 3, we compare the energy spectrum of Mrk 180 obtained using the EGMF models MHDy and MHDz together with the "broken" power-law initial spectra. We obtain a reduction of both point-like and halo intensities for the MHDy realization of EGMF which is characterized by stronger and less localized magnetic fields. As one can see, the strength of the perpendicular component of EGMF in the MHDy realization is almost an order of magnitude higher than in the MHDz case. This results in a reduction of the halo component, especially at lower energies. Nevertheless, for both realizations of the magnetic field structure, Mrk 180 remains a very promising case for the experimental detection of the halo in the TeV energy range. A similar result is obtained for 1ES 2344+514 [6].

III. DISCUSSION

We have studied blazar halos generated by deflections of the charged component of electromagnetic pair cascades. The intensity of these blazar halos depends mainly on the strength and the structure of the EGMF: Halos with detectable intensity require very weak EGMFs, comparable to those found in the MHDz simulations of Ref. [5].

Another necessary condition for the observability of halos is the extension of the source energy spectrum above $\sim 10^{14}$ eV. Such a high energy extension of the source spectrum may be generated by high energy protons interacting with background photons in the source or emitting synchrotron or curvature radiation. Note however that the acceleration of hadrons in the source does not necessarily lead to a pronounced ultrahigh energy tail of the accompanying gamma-ray spectrum. For instance, in the case of hadrons accelerated close to the core of the AGN, high energy gamma-rays start pair cascades on the background of ultraviolet photons. As a result, the spectrum of gamma-rays leaving the source is essentially cut-off at 10^{13} eV, for an example see e.g. Ref. [9]. Thus, the maximal energies assumed in the present work for the photons leaving the source rather correspond to acceleration in larger volumes, filled with less dense photon backgrounds and weaker magnetic field than close to the AGN core. Typical examples for

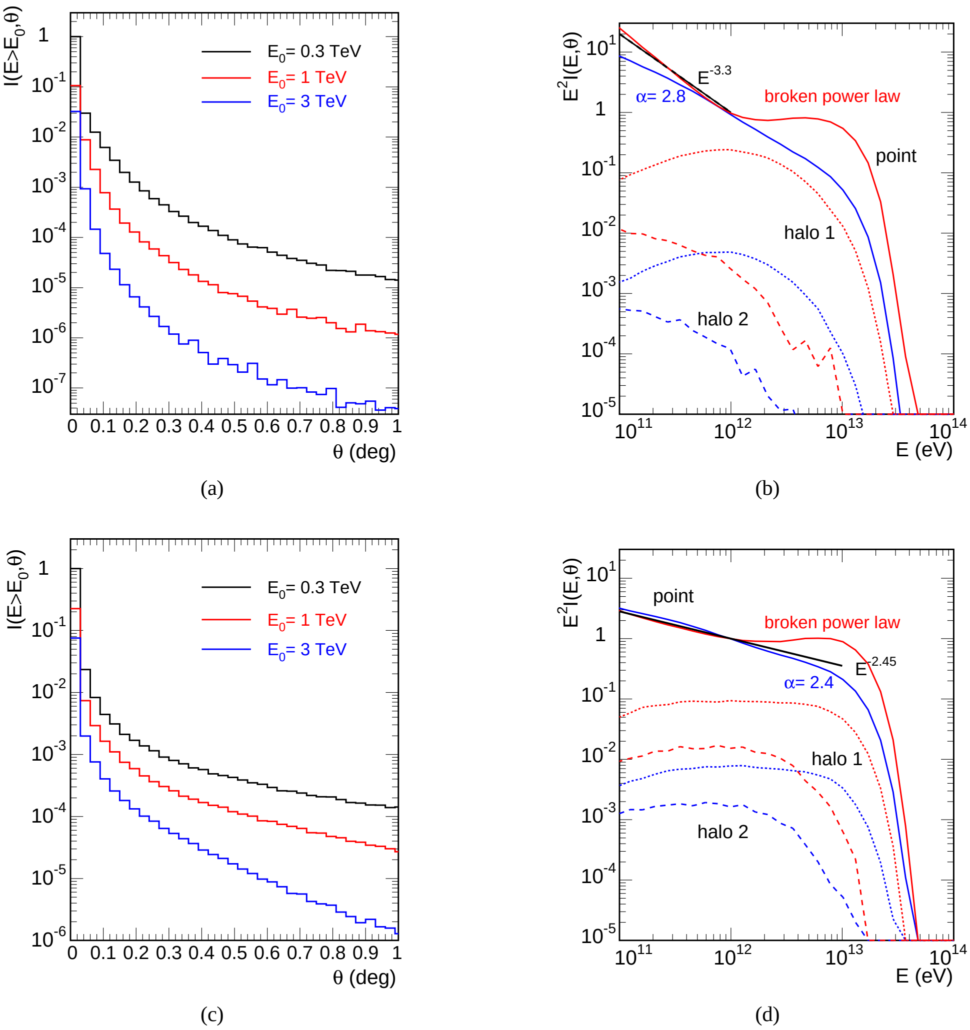

Fig. 1. Top: Mrk 180 (left panel: θ-dependence of integral intensity for the "broken" power-law initial spectrum with $\gamma_1 = 3.5$, $\gamma = 1.8$ and $E_b = 2\,\text{TeV}$; right panel: differential energy spectra for three angular bins for the power-law source spectrum with $\gamma = 2.8$ and for the "broken" power-law case), bottom: Mrk 501 (left panel: θ-dependence of integral intensity for the "broken" power-law initial spectrum with $\gamma_1 = 2.4$, $\gamma = 2.0$ and $E_b = 5\,\text{TeV}$; right panel: differential energy spectra for three angular bins for the power-law source spectrum with $\gamma = 2.4$ and for the "broken" power-law case); for all cases $E_{\max} = 10^{17}$ eV.

such a scenario are the acceleration of protons in the outer or radio jets of AGNs.

In the most optimistic cases, the halo component found reaches 10% of the point-like component and may be already detected or excluded by current IACTs. An observation of blazar halos would provide valuable information on the EGMF along the line-of-sight to the source and on the minimal luminosity emitted above the pair creation threshold. Moreover, a halo detection would point to an unbeamed emission of the high-energy part of the source photon spectrum, providing evidence for a different acceleration and emission mechanism than the standard leptonic one.

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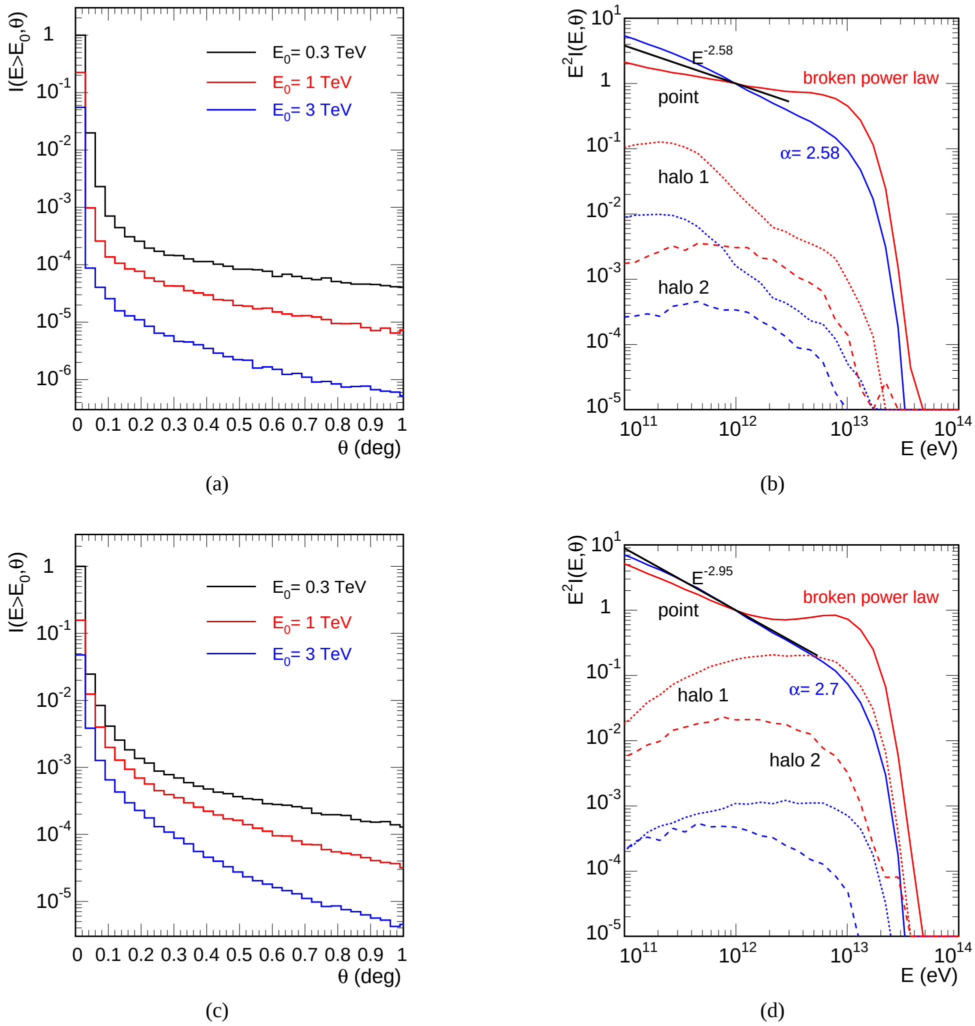
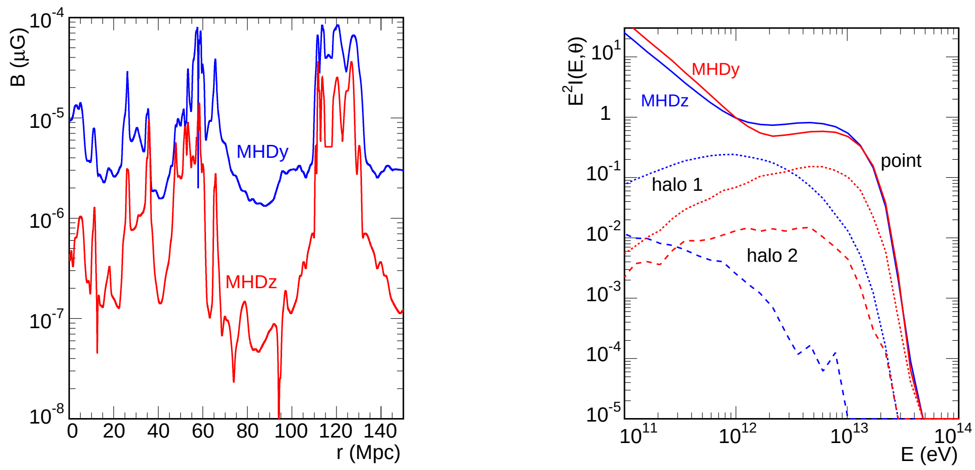


Fig. 2. top: 1ES1959+650, (left panel: θ-dependence of integral intensity for the "broken" power-law initial spectrum with $\gamma_1 = 2.6$, $\gamma = 1.8$ and $E_b = 3\,\mathrm{TeV}$; right panel: differential energy spectra for three angular bins for the power-law source spectrum with $\gamma = 2.58$ and for the "broken" power-law case), bottom: 1ES2344+514 (left panel: θ-dependence of integral intensity for the "broken" power-law initial spectrum with $\gamma_1 = 2.7$, $\gamma = 1.7$ and $E_b = 5\,\mathrm{TeV}$; right panel: differential energy spectra for three angular bins for the power-law source spectrum with $\gamma = 2.7$ and for the "broken" power-law case).



(a) (b)

Fig. 3. Left: The magnetic field $B_\perp$ perpendicular to the line-of-sight towards Mrk 180. Right: Comparison of differential energy spectra for three angular bins for two realizations of EGMF (MHDy [red] and MHDz [blue]) for Mrk 180.