Abstract. Indirect searches for dark matter annihilation or decay products in the cosmic-ray spectrum are plagued by the question of how to disentangle a dark matter signal from the omnipresent astrophysical background. One of the practically background-free smoking-gun signatures for dark matter would be the observation of a sharp cutoff or a pronounced bump in the gamma-ray energy spectrum. Such features are generically produced in many dark matter models by internal Bremsstrahlung, and they can be treated in a similar manner as the traditionally looked-for gamma-ray lines. Here, we discuss prospects for seeing such features with present and future Atmospheric Cherenkov Telescopes.

1. Introduction

Indirect dark matter (DM) searches aim at seeing an excess in cosmic rays from the annihilation or decay of DM in the Galactic halo [1]. Very often, indirect searches focus on secondary photons from the fragmentation of hadronic annihilation products. The corresponding spectra are rather broad and peak at energies much lower than the DM mass \(m_\chi\), which generically makes a convincing claim of a DM detection above the astrophysical backgrounds difficult. In many models, however, pronounced spectral features are expected at the kinematic endpoint \(E_\gamma = m_\chi\); they include monochromatic gamma-ray lines [2], sharp steps or cutoffs [3] as well as pronounced bumps [5]. The type and strength of these features are intricately linked to the particle nature of DM; a detection would thus not only allow for a convincing discrimination from astrophysical backgrounds but also to determine important DM model parameters like the value of \(m_\chi\). So far, only line-signals have explicitly been searched for [3]—despite the fact that they are loop-suppressed and thus generically subdominant compared to other spectral signatures [5]. Here, we discuss a general method to search for sharp spectral features in gamma-ray observations. Concentrating on DM models with a large internal Bremsstrahlung (IB) component, and on observations with Imaging Atmospheric Cherenkov Telescopes (IACTs), we derive projected limits and prospects to see such signatures with current and future instruments.
Table 1. DM benchmark models used in our analysis as examples for the typical spectral endpoint features to be expected in WIMP annihilations. For these particular models, we also state the annihilation channel that is most important in this context, as well as mass and total annihilation rate for thermally produced DM. See text and Ref. [10] for further details about the DM models and Fig. 1 for the corresponding photon spectra.

| DM particle | $m_\chi^{th}$ [TeV] | $\langle \sigma v \rangle^{th}$ [cm$^3$s$^{-1}$] | relevant spectral channel feature |
|-------------|------------------|-----------------|-------------------------------|
| $\gamma\gamma$ | any WIMP $\mathcal{O}(0.1–10)$ | $\mathcal{O}(10^{-30})$ | $\gamma\gamma$ line |
| KK          | $B^{(1)}$        | 1.3             | $\ell^+\ell^-\gamma$ FSR step |
| BM3 neutralino | 0.23             | $9 \times 10^{-29}$ | $\ell^+\ell^-\gamma$ IB bump |
| BM4 neutralino | 1.9              | $3 \times 10^{-27}$ | $W^+W^-\gamma$ IB bump |

Figure 1. Photon spectra for the DM benchmark models of Tab. 1. Dashed lines show the same spectra smeared with a Gaussian of width $\Delta x/x = 0.1$. From Ref. [10].
(although in some cases much stronger line signals are possible). (2) As an example for a step-like feature we use the gamma-ray spectrum expected from annihilating Kaluza-Klein (KK) DM in models of universal extra dimensions [11]. Its total gamma-ray annihilation spectrum at high energies is dominated by final state radiation (FSR) off lepton final states, and the shape of the spectrum $dN/dx$, with $x = E_\gamma/m_\chi$, turns out to be essentially independent of $m_\chi$ and other model parameters [4]. (3) Pronounced bump-like features at $E \approx m_\chi$ may arise from IB in the annihilation of neutralino DM [5]. Here, BM3 is a typical example for a neutralino in the stau co-annihilation region, where photon emission from virtual sleptons greatly enhances the photon spectrum at high energies; BM4 refers to a situation in which IB from $W^\pm$ final states dominates.

In Tab. 1 we shortly summarize the properties of the DM benchmark models described above, including for completeness the actual DM mass and total annihilation rate needed to obtain the observed relic density for thermally produced DM. Note, however, that we essentially treat these values as free parameters in our analysis and that we are rather interested in the spectral shape of the annihilation signal, represented by $dN/dx$; in Fig. 1 we show these spectra for a direct comparison.

3. Results and discussion
In Fig. 2 we show our results for the expected 2$\sigma$ upper limits (thick lines) on the above DM models as well as the variance of these limits among the mock data sets. We find that in particular IB features in the spectrum (right panel) have the potential to constrain the annihilation rate at least down to values typically expected for thermal production, $\langle \sigma v \rangle \sim 3 \cdot 10^{-26}$ cm$^3$s$^{-1}$, already for modest assumptions about the DM distribution. For models with very large IB contributions like BM3, we find that our method would provide even stronger limits on $\langle \sigma v \rangle$ than what was obtained by the H.E.S.S. analysis of the Galactic center region.
assuming annihilation into $\bar{b}b$ [12].

For the case of not too strongly pronounced endpoint features (like line signals in most models or the step for Kaluza-Kleđn DM), secondary photons will usually be more powerful in constraining the total annihilation rate $\langle \sigma v \rangle$. However, in case of an adiabatically compressed profile our limits could improve by maybe two orders of magnitude, as demonstrated for gamma-ray lines in the left panel. As shown in the central panel of Fig. 2 the future CTA should be able to place limits about one order of magnitude stronger than currently possible, and the proposed DMA could further improve these by another factor of ten.

Finally, we would like to stress that our limits in general provide rather complementary information on the DM nature and cannot easily be compared with limits on secondary photons. In any case, from the point of view of indirect DM searches, the detection of the kinematic cutoff will be much more interesting than the detection of secondary photons, because they would provide rather unambiguous evidence for the DM nature of the signal as well as allow one to determine important parameters like the DM mass. An obvious extension of the approach presented here is to apply it to the discrimination of models [13].

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References

[1] G. Bertone, D. Hooper, J. Silk, Phys. Rept. 405 (2005) 279.
[2] L. Bergström, P. Ullio and J. H. Buckley, Astropart. Phys. 9 (1998) 137 [arXiv:astro-ph/9712318].
[3] A. Birkedal, K. T. Matchev, M. Perelstein and A. Spray, arXiv:hep-ph/0507194.
[4] L. Bergström, T. Bringmann, M. Eriksson and M. Gustafsson, Phys. Rev. Lett. 94 (2005) 131301 [arXiv:astro-ph/0410359].
[5] T. Bringmann, L. Bergström and J. Edsjö, JHEP 0801 (2008) 049 [arXiv:0710.3169 [hep-ph]].
[6] A.A. Pullen, R.R. Chary, M. Kamionkowski, Phys. Rev. D 76 (2007) 063006 [Erratum-ibid. 83 (2011) 029904] [arXiv:astro-ph/0610295]; F. A. Aharonian et al. [HEGRA Collaboration], Astron. Astrophys. 400, 153 (2003) [astro-ph/0302347]; A. A. Abdo et al., Phys. Rev. Lett. 104 (2010) 091302 [arXiv:1001.4836 [astro-ph.HE]]; G. Vertongen and C. Weniger, JCAP 1105 (2011) 027 [arXiv:1101.2610 [hep-ph]].
[7] F. Aharonian et al. [H.E.S.S. Collaboration], Astron. Astrophys. 457 (2006) 899 [arXiv:astro-ph/0607333].
[8] The CTA Consortium, arXiv:1008.3703 [astro-ph.IM].
[9] L. Bergström, T. Bringmann and J. Edsjö, Phys. Rev. D 83 (2011) 045024 [arXiv:1011.4514 [hep-ph]].
[10] T. Bringmann, F. Calore, G. Vertongen and C. Weniger, Phys. Rev. D 84 (2011) 103525 [arXiv:1106.1874 [hep-ph]].
[11] G. Servant and T. M. P. Tait, Nucl. Phys. B 650 (2003) 391 [arXiv:hep-ph/0206071].
[12] A. Abramowski et al., Phys. Rev. Lett. 106, 161301 (2011) [arXiv:1103.3266 [astro-ph.HE]].
[13] T. Bringmann, F. Calore, G. Vertongen and C. Weniger, work in progress; see also, e.g., M. Perelstein and B. Shakya, JCAP 1010 (2010) 016 [arXiv:1007.0018 [astro-ph.HE]].