

Novel gamma-ray features from dark matter cascade processes involving scalars and fermions as intermediate states

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Abstract. We present novel gamma-ray features that are almost exclusively a consequence of kinematical considerations in one-step cascade processes. These features arise from relativistic effects on final state photons from decaying intermediate states. Depending on the spin of the intermediate state the specific shape of the signal varies: a scalar or Majorana fermion intermediate state produces gamma-ray boxes, whereas a Dirac fermion intermediate state produces gamma-ray triangles. We refer to physical realisations that produce such features. Finally, we illustrate their strong constraining power using data drawn from the Fermi-LAT instrument.

1. Introduction

Among the different dark matter (DM) candidates, weakly interacting massive particles (WIMPs) are one of the best studied ones. The majority of WIMP scenarios predict dark matter masses between the ranges of a few GeV up to a few TeV. As a consequence of their freeze-out production mechanism the annihilation of these particles into standard model (SM) particles is guaranteed. Dark matter indirect searches aim to observe a contribution to the astrophysical background radiation of different messengers, from dark matter annihilations. In this work we focus on novel strategies for the search of dark matter hints on gamma-ray data.

Since dark matter is not subject to electromagnetism, it cannot emit photons at tree level. Hence, photons can be emitted either promptly via loop or as an end product of annihilations into other SM particles, e.g. pion decay or inverse Compton scattering, among others. Although the astrophysical background is very bright it remains smooth and a hard spectral feature would be a clear hint for dark matter. Currently there are three known methods for the production of spectral features. Gamma-ray lines are produced by loop induced annihilations into monochromatic photons, internal bremsstrahlung signals can produce a sharp feature near the kinematical end of the emitted spectrum; lastly gamma-ray boxes [1, 2] are emitted in one-step cascade processes involving relatively short-lived intermediate states which decay in-flight into photons. In this work, we elaborate on the latter by analysing the phenomenology of one-step cascades involving fermions.



2. Phenomenology of cascade processes

We consider the case where dark matter χ annihilates¹ into intermediate states ϕ which in turn decay into at least one photon: $\chi\chi \rightarrow \phi\phi \rightarrow 2\gamma 2\xi$, where ξ is any state required by the underlying model. The energy spectrum of the radiated photon in the rest frame of ϕ is monochromatic with an energy given by:

$$E_{\gamma}^{\text{r.f.}} = \frac{1}{2}\delta_{\xi\phi}m_{\chi} \quad \text{with} \quad \delta_{ij} = 1 - \frac{m_i^2}{m_j^2}.$$

However, unless $m_{\chi} \approx m_{\phi}$ the particle ϕ is produced with a non-vanishing momentum in the lab frame –where dark matter is assumed at rest– and the energy of the photon is modified, depending on the direction of emission, to a value between the kinematical ends

$$E_{\pm} = \left(1 \pm \sqrt{\delta_{\phi\chi}}\right) \delta_{\xi\phi} \frac{m_{\chi}}{2}. \quad (1)$$

This result follows only from kinematical considerations and up to this point no assumptions on the particle nature of the involved states has been made.

The shape of the spectrum between the kinematical ends given in Eq. 1 depends on the angular distribution of the emitted photons which can be parametrised as [3]

$$\frac{dN}{d\cos\theta} = \frac{1}{2} (1 + \alpha \cos\theta), \quad (2)$$

where α parametrises the spin polarisation of the intermediate state ϕ , and θ is the angle between the photon momentum in the centre-of-mass frame and the momentum of ϕ in the lab frame. When boosted to the lab frame, the photon energy is shifted depending on the angle of emission θ . Therefore, the shape of the signal between the kinematical ends is dictated by the angular distribution of the photons, as we illustrate in the following paragraphs.

We discuss separately the cases where ϕ is either a scalar or a Majorana fermion, or a Dirac fermion:

Scalar or Majorana fermion

If the state is a scalar, the photon emission in the rest frame is isotropic, since there is no preferred direction. In the lab frame this translates to no preferential emission angle θ , and so $\alpha = 0$. Hence, every energy value between the kinematical ends is equally populated. This gives rise to gamma-ray boxes as discussed in detail in [1, 2]. This argument is also valid for Majorana fermions due to their particle nature.

Dirac fermion

In contrast to the previous case, if ϕ is a Dirac fermion, there is clearly a preferred direction and so $\alpha \in [-1, 1]$. The exact value for α depends on the specific physical model in which this scenario is realised. If $\alpha > 0$ photons are emitted preferentially in forward direction and the spectrum between the kinematical ends is described by an up-going slope, whereas if $\alpha < 0$ the preferred direction is backwards and the spectrum is described by a down-going slope. We call these features gamma-ray triangles. For a more complete discussion we refer to [4].

¹ Throughout this work we will focus exclusively on dark matter annihilations. The phenomenology for dark matter decays follows in an analog fashion.

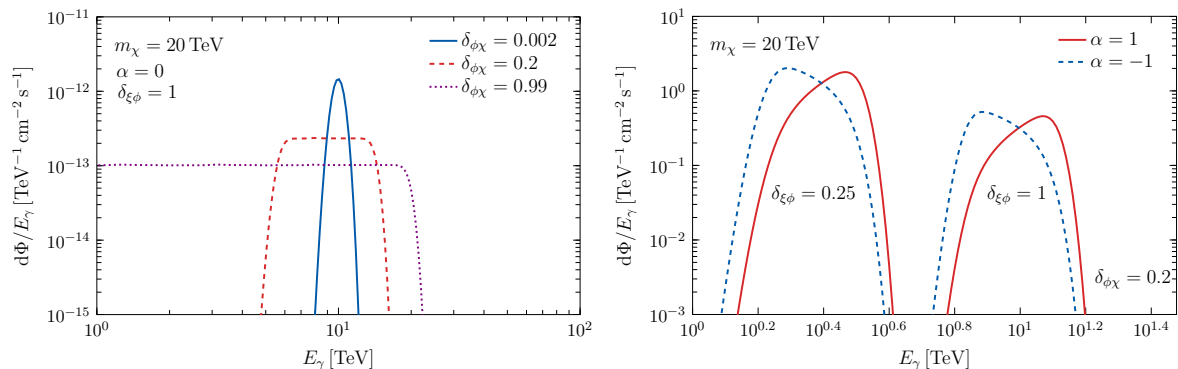


Figure 1. The photon spectra from Eq. 3 for different parameters $\delta_{\phi\chi}$, $\delta_{\xi\phi}$ and α with a dark matter mass $m_\chi = 20$ TeV. The left panel shows gamma-ray boxes for the parameters $\alpha = 0$ and $\delta_{\xi\phi} = 1$ whilst varying the width parameter $\delta_{\phi\chi} = 0.002, 0.2, 0.99$ in blue, red dashed, and purple dotted respectively. The right panel shows gamma-ray triangles with $\delta_{\phi\chi} = 0.2$, two different slopes $\alpha = 1, -1$ in red, blue dashed respectively, and with a positioning at high $\delta_{\xi\phi} = 1$ and low $\delta_{\phi\chi} = 0.25$ energies.

The photon spectrum emitted by any of the aforementioned cascade scenarios is parametrised by $\delta_{\phi\chi}$, $\delta_{\xi\phi}$ and α . The parameter $\delta_{\phi\chi}$ controls the relative width $\Delta E \equiv (E_+ - E_-)$ and the parameter $\delta_{\xi\phi}$ controls the positioning of the centre of the signal $E_c \equiv (E_+ + E_-)/2$:

$$\frac{E_c}{m_\chi} = \frac{\delta_{\xi\phi}}{2} \quad \text{and} \quad \frac{\Delta E}{E_c} = 2\sqrt{\delta_{\phi\chi}}.$$

Furthermore the slope of the signal is parametrised by α .

Summarising the discussion above, the photon spectrum in the lab frame is given by:

$$\frac{dN_\gamma}{dE_\gamma} = \frac{N_\gamma}{\delta_{\phi\chi} \delta_{\xi\phi} m_\chi} \left(\sqrt{\delta_{\phi\chi}} - \alpha + \frac{2\alpha}{\delta_{\xi\phi}} E_\gamma \right) \Theta(E_\gamma - E_-) \Theta(E_+ - E_\gamma) \quad (3)$$

with the Heaviside step function $\Theta(x)$, the dark matter mass m_χ and the number of photons N_γ emitted by a single decay of ϕ . We plot this spectrum for a dark matter mass of $m_\chi = 20$ TeV in in Fig. 1. The left panel shows gamma-ray boxes $\alpha = 0$ with $\delta_{\xi\phi} = 1$ and varying the width parameter $\delta_{\phi\chi} = 0.002, 0.2, 0.99$ for narrow, intermediate, and wide cases respectively. The right panel displays gamma-ray triangles for the two extreme cases of the slope parameter $\alpha = 1, -1$ as well as for two values of the positioning parameter $\delta_{\xi\phi} = 0.25, 1$ with $\delta_{\phi\chi} = 0.2$. Note that these results are independent of the particle nature of dark matter as long as the annihilation channel is permitted by the underlying model.

3. Models

Models that feature gamma-ray boxes are usually based on the breaking of global symmetries. The models discussed in [2, 5, 6] invoke the Peccei-Quinn [7] mechanism and the resulting pseudo-scalars are suited as intermediate states. Here, Dirac dark matter annihilates into scalars s and/or pseudo-scalars a through the channels $\chi\bar{\chi} \rightarrow aa$, $\chi\bar{\chi} \rightarrow ss$ and $\chi\bar{\chi} \rightarrow as$. The two former channels are p-wave and the latter is s-wave, this means that the annihilation into a scalar and a pseudo-scalar is the dominating one today. The pseudo-scalar decays into photons through anomalies with a branching ratio of a few up to a hundred percent depending on its mass m_a and on the exact value of the anomaly coefficients c_i .

Additionally, the model constructed in [8] can also emit gamma-ray boxes. This model produces

a scalar s and a pseudo scalar a in a similar fashion as the previous one. This framework aims at explaining experimental data restricting the masses of the involved particles to $m_\chi \simeq \mathcal{O}(\text{TeV})$, $m_s \ll m_\chi$ and $m_a = 360 - 800 \text{ MeV}$, which means only wide boxes can be produced. Here, the branching ratio of a into photons is small $\text{BR}(a \rightarrow \gamma\gamma) \simeq 10^{-3}$. However, this model allows a Sommerfeld enhancement of $\simeq 10^3$ which compensates the suppression of the small branching ratio.

For the production of gamma-ray triangles there are to our knowledge no models yet. An ongoing work [4] will introduce a physical realisation where these features are present. In this work we sketch the main properties in a more superficial manner. The intermediate state is required to be a Dirac fermion –which from now on will be referred as ψ in order to distinguish it from the scalar and Majorana fermion case ϕ – thus, dark matter has to be also Dirac. Furthermore, the only possible decay mode of a fermion into photons is $\psi \rightarrow \gamma\nu$ where ν is another fermion with a lighter mass than that of the intermediate state $m_\nu < m_\psi$. Additionally, the particle ψ has to be produced with a specific helicity otherwise the preferred direction of emission would be arbitrary resembling the case where the intermediate state is Majorana. This means that the Yukawa interaction for $\psi \rightarrow \gamma\nu$ has to be chiral. Lastly, the annihilation of dark matter has to be a self-annihilation $\chi\chi \rightarrow \psi\psi$ in order to produce ψ with a specific helicity and not its antiparticle $\bar{\psi}$ with the opposite helicity, countering any anisotropic photon emission by producing a mirrored signal. This also means that the same process involving antiparticles $\bar{\chi}\bar{\chi} \rightarrow \bar{\psi}\bar{\psi}$ has to be suppressed. In [4] this is achieved by imposing an asymmetry between dark matter particle and its antiparticle.

4. Comparing with data

Searching for these signals in existing data as well as drawing limits is not an easy task. In this work we illustrate in a simplistic manner the constraining power of such signals using Fermi-LAT data.² We present in Fig. 2 limits drawn using 2.3 yr Fermi-LAT data from [9] (centre region). We present limits for narrow $\delta_{\phi\chi} = 0.001$, intermediate $\delta_{\phi\chi} = 0.25$ and wide $\delta_{\phi\chi} = 0.99$ cases in the left, centre and right panels respectively. In each panel we present limits for $\alpha = 0$ (orange), $\alpha = 1$ (dashed blue), and $\alpha = -1$ (dot-dashed green). The limits were drawn using sliding energy windows $[\bar{E}/\sqrt{\epsilon}, \bar{E}\sqrt{\epsilon}]$ with $\bar{E} = E_+(E_-)$ for $\alpha = 0, 1(-1)$ and $\epsilon = 2$. For gamma-ray triangles we assume $m_\nu = 0$.

For the narrow case the difference between the three different slopes is negligible since the shape of the signal gets lost due to the resolution of the instrument. Whereas for the wide case the difference is at its largest since a signal with $\alpha = -1$ is considerably softer than the other cases.

5. Conclusions

We presented and expanded on gamma-ray features coming from one-step cascade annihilations. Gamma-ray boxes and triangles are features that arise as artefacts of kinematics, leaving only the exact shape of the feature dependent of the spin of the intermediate state. The phenomenology of these features was described with the help of three key parameters which describe the width, placement, and shape of the signal. Additionally, we discussed the main features of physical models in which gamma-ray boxes are present as well as sketched the main properties of a model in order to produce gamma-ray triangles. Lastly we illustrated, using Fermi-LAT data, that such signals can be a strong tool when testing models capable of producing such signals.

² We refer to [1, 2, 10] for a more thorough analysis using gamma-ray boxes and to [4] for gamma-ray triangles.

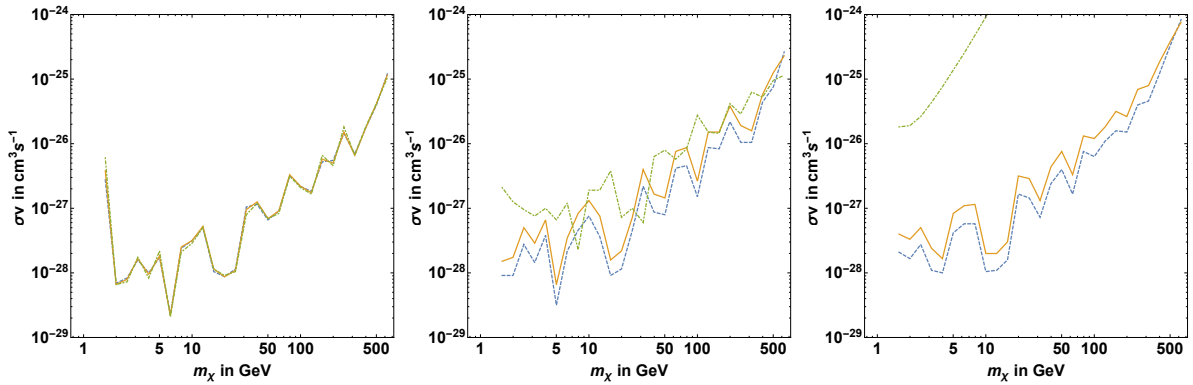


Figure 2. Upper limits for narrow, intermediate and wide cases in the left, centre and right panel respectively using 2.3yr Fermi-LAT data. Each panel shows the limits for gamma-ray boxes $\alpha = 0$ (orange) and for gamma-ray triangles $\alpha = 1$ (dashed blue) and $\alpha = -1$ (dot dashed green).

Acknowledgments

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