Electroweak fragmentation functions for dark matter annihilation

Leila Ali Cavasonza[1], *Michael Krämer*[1,2], *and Mathieu Pellen*[1]

[1] *Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, D-52056 Aachen, Germany*

[2] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94025, USA*

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Electroweak corrections are relevant for dark matter indirect detection predictions. The quality of the fragmentation function approximation to describe electroweak gauge boson radiation is examined in two concrete models. For models with Majorana fermion dark matter annihilation into light fermions, the fragmentation function approximation does not work, due to the helicity suppression of the lowest-order cross section. For other models, like those with vector dark matter, fragmentation functions provide very reliable results for dark matter with masses $M_{\rm DM} \gtrsim 500\,{\rm GeV}$.

1 Introduction

In dark matter indirect detection experiments one searches for dark matter annihilation products, including antimatter particles like positrons and antiprotons, which propagate through the galactic halo and which can be detected in astrophysical experiments at the earth.

As pointed out in the literature [1, 2, 3, 4, and refs. therein], electroweak (EW) radiation from the primary dark matter annihilation products can significantly alter the spectra of the secondary Standard Model particles, that may be detected at the earth. The decay of the EW bosons will modify the spectra of the primary annihilation products and, more importantly, will always produce the complete spectrum of stable SM particles, irrespective of the model-specific composition of the primary annihilation products.

Many models provide dark matter candidates with masses in the TeV-range. For such heavy dark matter, soft and collinear electroweak gauge boson emission from the relativistic final-state particles is enhanced by Sudakov logarithms $\ln^2(M_{\rm DM}^2/M_{\rm EW}^2)$ [5], where $M_{\rm DM}$ and $M_{\rm EW}$ are the mass of the dark matter candidate and of the electroweak gauge boson, respectively. The fragmentation function formalism [2, and refs. therein] provides a simple and model-independent approximation to describe the logarithmically enhanced contributions due to EW radiation. Note that the model-dependent gauge boson emission off initial and intermediate state particles is not reproduced by the fragmentation function approximation.

In the following we examine the quality of the fragmentation function approximation. To this end, we have compared the predictions obtained for the flux at the earth using the fragmentation function approximation against those obtained from an exact calculation of Z-boson emission. To perform the comparison we have chosen two concrete models of dark matter: a simplified version of the Minimal Supersymmetric Model (MSSM) [6, 7], and a simplified Universal Extra Dimension (UED) model [8, 9]. In these models the dark matter candidates are a pure bino neutralino, $\tilde{\chi}^0$, and the first Kaluza-Klein excitation of the SU(2) gauge boson, $B^{(1)}$, *i.e.* a Majorana fermion and a vector boson, respectively. For simplicity we focus on the particular case where the dark matter particles annihilate at lowest order into electron-positron pairs only. To assess the quality of the fragmentation function approximation [10], which only describes the logarithmically enhanced contributions to Z-boson radiation off the finale state, we have performed comparisons of the energy spectra of the Z bosons and of the spectra of positrons and anti-protons at the earth after the propagation through the galactic halo. We have obtained the secondary particles fluxes using PYTHIA 8 [11, 12] and implemented the propagation through the galactic halo using a Green functions formalism [13, and refs. therein].

In this proceedings contribution we show that the fragmentation function approach reproduces well the exact result for vector dark matter annihilation (the UED case), while the approximation does not work for the annihilation of Majorana fermion dark matter into light fermions (the MSSM case). This is due to the fact that the annihilation of neutralinos into a lepton pair is helicity suppressed [14, 15, 16] and that the emission of soft and collinear gauge bosons from the final state particles, included in the fragmentation function approximation, is not sufficient to lift this helicity suppression [3]. Hence, the fragmentation function approximation provides a simple and reliable technique to obtain realistic predictions for dark matter indirect detection for models where the annihilation is not suppressed at the lowest order.

2 Comparison and results

The fragmentation function approximation does not reproduce the correct result for Majorana fermion annihilation as anticipated [10]. Therefore, we consider here only the spectra for positrons and antiprotons from the annihilation of vector dark matter in the universal extra dimension model after propagation through the galactic halo. We compare the results from the full $(2 \to 3)$ calculation, $B^{(1)}\,B^{(1)} \to e^+e^-(Z \to \text{SM particles})$ and the fragmentation function approximation. In Fig. 1 the positron spectra after parton shower and propagation are displayed. The fragmentation function approximation provides an accurate description of the positrons from the Z-boson decay. However, as the cross section of the $(2 \to 3)$ process is a genuine electroweak higher-order contribution of $\mathcal{O}(\alpha \ln^2(M_{\rm DM}^2/m_Z^2))$, and thus highly suppressed by comparison to the leading-order annihilation, the amount of additional positrons is small compared to those produced in the $(2 \to 2)$ process The small dip in the fragmentation function prediction at high energies is a remnant of the kinematics of the $(2 \to 2)$ process and is disappearing as $M_{\rm DM}/m_Z$ increases. In our simple leptophilic model set-up, antiprotons are generated exclusively from Z-boson decay. As the fragmentation function provides a good approximation to the Z-boson spectrum of the exact calculation [10], the flux of antiprotons is also expected to be reproduced well. This is indeed born out by the explicit calculation presented in Fig. 2. We find that the exact $(2 \to 3)$ calculation and the fragmentation function approach agree within 10% for $M_{\rm DM} \gtrsim 500\,\text{GeV}$. This result is further supported by the comparison of the fragmentation function result against the analytical expression for the exact $(2 \to 3)$ calculation, see Ref.[10].

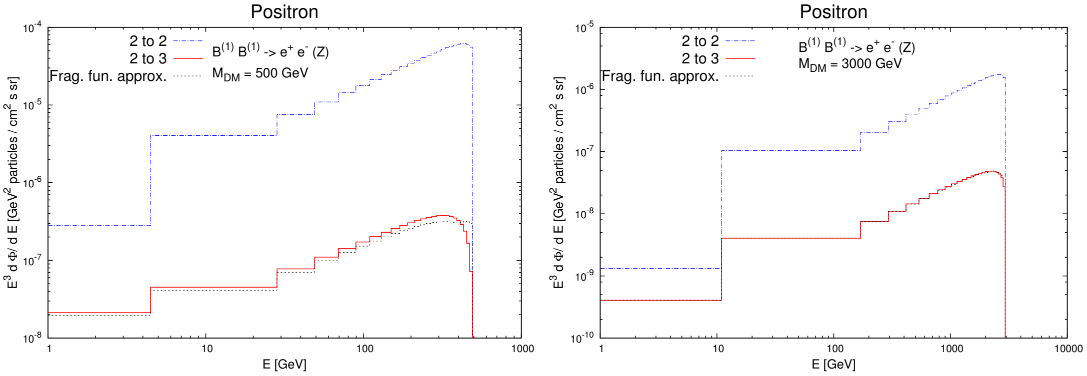

Figure 1: Positron energy spectra for $M_{\rm DM} = 500$, 3000 GeV in the UED case after propagation.

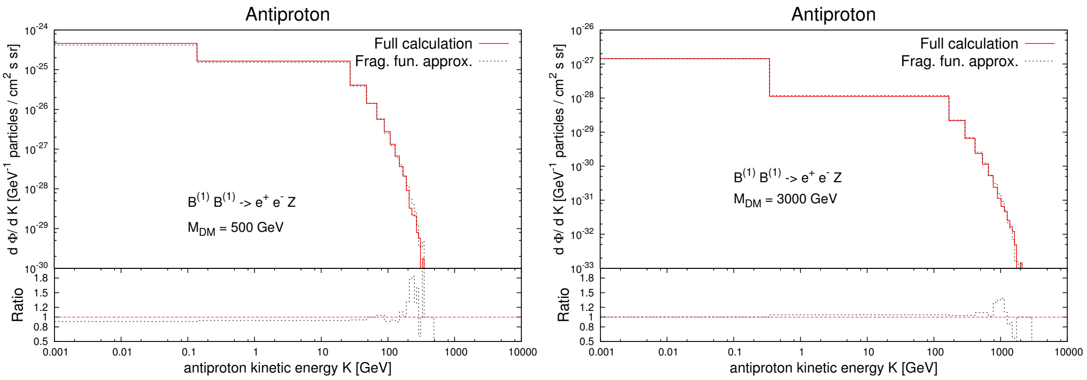

Figure 2: Antiproton spectra for $M_{\rm DM} = 150$, 3000 GeV in the UED case after propagation.

3 Conclusions

We have examined the quality of the fragmentation function approximation for two specific simple DM models [10], by comparing the primary energy spectra and fluxes after the evolution of the annihilation products and propagation through the galactic halo. We find that fragmentation functions fails to reproduce the behaviour of the complete calculation for models with Majorana fermion annihilation into light fermions. This is due to the fact that the soft/collinear contribution to Z-boson radiation, included in the fragmentation function approximation, is not sufficient to lift the helicity suppression of the lowest-order cross section. By contrast, we find that the fragmentation function approach is working very well for models that do not suffer from helicity suppression at the lowest order, like vector dark matter annihilation in models with universal extra dimensions. Specifically, we find that the particle fluxes after probation through the galactic halo obtained from the exact ($2 \to 3$) calculation and the fragmentation function approach agree to better than 10% for $M_{\rm DM} \approx 500\,{\rm GeV}$ and to better than 2% for $M_{\rm DM} \approx 1\,{\rm TeV}$. The fragmentation function formalism thus provides a simple framework to obtain predictions for astrophysical experiments for models where the lowest-order annihilation cross section is not suppressed.

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