Gamma-ray lines may reveal the CP nature of the dark matter particle

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Abstract. Determining the fundamental properties of the dark matter is one of the most important open problems in particle physics today. If the dark matter particle has spin zero, one of these properties is its CP nature. That is, whether it is CP-even (scalar), CP-odd (pseudoscalar), or if its interactions violate CP. In this paper, we show that the observation of \( \gamma \)-ray lines arising from the decay of a spin-zero dark matter particle could be used to discriminate among these possibilities. We consider a general setup where dark matter decay is induced by effective operators and demonstrate that, due to gauge invariance, there exists correlations among the branching ratios into gauge boson final states (\( \gamma\gamma \), \( \gamma Z \), \( W^+W^- \), \( ZZ \)) that depend on the mass and the CP properties of the dark matter. Consequently, the future observation of \( \gamma \)-ray lines may in principle be used to establish the CP nature of the dark matter particle.

Keywords: cosmology of theories beyond the SM, dark matter theory

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1 Introduction

Even though dark matter accounts for about 25% of the energy density of the Universe [1], we know almost nothing about it. A new elementary particle, not currently known and not included in the Standard Model, is required to explain this exotic form of matter, but it is not at all clear what particle it is. In fact, one of the most important open problems in particle physics today is precisely that of identifying the dark matter particle or, equivalently, determining its fundamental properties.

To that end, the first step would be the detection of the dark matter particle by non-gravitational means. Currently, dark matter is being searched for in direct and indirect dark matter detection experiments [2–6], as well as at the LHC [7, 8]. A dark matter signal may be detected anytime, so it is crucial to be prepared to extract from it as much information as possible about the nature of the dark matter particle. Several studies have been carried out along these lines — see e.g. [9–15]. They generally aim at measuring the dark matter mass and the relevant cross section (or lifetime), which would certainly help identifying the dark matter particle. But couldn’t we also unveil some of its fundamental properties? Very few works have addressed this important issue. In [16, 17] it was shown that it may be possible to determine whether the dark matter particle is identical to its antiparticle while in [18, 19] it was demonstrated that the spin of the dark matter particle could be revealed. These analyses were all based on the observation of dark matter signals in future direct detection experiments.

In this work we address for the first time the possibility of determining the CP properties of the dark matter particle. We show that it is in principle feasible to find out whether the dark matter particle is a scalar, a pseudoscalar, or if its interactions violate CP. Our proposal relies on the observation of γ-ray lines arising from the decay of a spin-zero dark matter particle ($\varphi \rightarrow \gamma \gamma$ and $\varphi \rightarrow \gamma Z$), and on the correlation between their branching ratios, which is enforced by gauge invariance. Specifically, we demonstrate that, within a generic framework in which dark matter decay is induced by effective operators, such correlation exists and depends on the mass and the CP nature of the dark matter. Thus, the future observation of γ-ray lines may be used to establish whether the dark matter particle is CP-even (scalar), CP-odd (pseudoscalar), or CP-violating, providing a decisive clue towards the identification of the dark matter particle.
2 Framework

Let us assume that future indirect detection experiments observe a γ-ray signal whose morphology is consistent with decaying [20–23] rather than annihilating dark matter. From a theoretical point of view, such a signal can be explained within the framework of effective field theory. At the end, the dark matter lifetime must be much larger than the age of the Universe [24], a fact that could be attributed to the scale suppression associated with higher dimensional effective operators. For definiteness, we will consider a dark matter particle, \( \varphi \), that has spin zero and is a singlet under the SM gauge group and assume that the detected dark matter signal features some prominent γ-ray lines. γ-ray lines have received a lot of attention in indirect detection analyses [25–28] because, being essentially free of astrophysical backgrounds, they provide a smoking-gun signature of dark matter. The most general effective Lagrangian that can induce the decay of \( \varphi \) into γ-ray lines is

\[
\mathcal{L} = \frac{a}{M_{pl}} \varphi B_{\mu\nu} B^{\mu\nu} + \frac{b}{M_{pl}} \varphi B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{c}{M_{pl}} \varphi W^I_{\mu\nu} W'^I_{\mu\nu} + \frac{d}{M_{pl}} \varphi W^I_{\mu\nu} \tilde{W}'^I_{\mu\nu} \tag{2.1}
\]

where \( M_{pl} \) is the Planck mass (an arbitrary scale \( \Lambda \) may be used instead), \( a, b, c, d \) are dimensionless coupling constants, and \( B_{\mu\nu} \) and \( W^I_{\mu\nu} \) are the strength-field tensors associated with \( U(1)_Y \) and \( SU(2) \), respectively, and \( \tilde{B}_{\mu\nu} \) and \( \tilde{W}^I_{\mu\nu} \) their corresponding dual tensors. Notice that all these operators have mass dimension 5. There are no operators at dimension 6 inducing the decay — the only possibility is the Weinberg operator multiplied by \( \varphi \), which does not produce γ-ray lines — whereas at dimension 7, the operators that may produce lines are all suppressed by the factor \( (v/M_{pl})^2 \) with respect to those we consider. The γ-ray lines could also be generated through loop-diagrams, e.g. via \( \varphi \) coupling to SM fermions, but in that case they are expected to be significantly suppressed with respect to the continuum contribution, a fact that would hinder the possibility of actually observing them.

Given this interaction Lagrangian, the CP nature of the dark matter is determined by the couplings \( a, b, c, d \) as follows: if \( b = d = 0 \), only the CP-even terms survive and we say that \( \varphi \) is a proper scalar (or CP-even); if \( a = c = 0 \), only the CP-odd terms survive and \( \varphi \) is a pseudoscalar (or CP-odd); in any other situation we would simultaneously have CP-even and CP-odd terms, which would imply CP violation.

Hence, one way in which the CP nature of the dark matter could be determined is by extracting these couplings directly from the observed γ-ray spectrum. For instance, if a fit to the spectrum were to require \( a, d \neq 0 \), CP violation would have been established. We advocate, however, a different approach based on the correlations among the branching ratios into different final states. The above Lagrangian induces the decay of \( \varphi \) into the following two-body final states: \( \gamma \gamma, \gamma Z, W^+W^\gamma, \) and \( ZZ \). The novel idea of this work is that, due to gauge invariance, there exists correlations among the branching ratios into these four final states that depend on the CP nature of the dark matter. Thus, the detection of signals consistent with the decay of a scalar dark matter particle into γ-ray lines could be used to determine whether the dark matter particle is CP-even, CP-odd or CP-violating.

3 Results

Let us now illustrate how such correlations differ according to the CP nature of the dark matter particle (see the appendix for the analytic expressions required to produce the figures).
Figure 1 shows, for $M_{DM} = 165$ GeV, scatter plots of $BR(\phi \rightarrow \gamma \gamma)$ versus $BR(\phi \rightarrow \gamma Z)$ in the left panel and of $BR(\phi \rightarrow \gamma \gamma)$ versus $BR(\phi \rightarrow W^+W^-) + BR(\phi \rightarrow ZZ)$ in the right panel. Three sets of points are shown in each panel, corresponding to the possible CP properties of the dark matter. The points denoted by CP-even (in red) were obtained by randomly varying $a$ and $c$ while setting $b = d = 0$. The points denoted by CP-odd (in blue) were obtained instead by randomly varying $b$ and $d$ while setting $a = c = 0$. Finally, the points denoted by CP violation (in green) correspond to randomly varying all four couplings — $a,b,c,d$. Notice that the CP-even and the CP-odd points lie along different ellipses on both planes, whereas the points featuring CP violation are spread over a much larger area. These figures already demonstrate the main point of this paper: the observation of such decays may provide direct information on the CP nature of the dark matter.

From the left panel, for instance, one can see that $BR(\phi \rightarrow \gamma \gamma)$ has a maximum of about 60% for a CP-even scalar and of about 90% for a CP-odd or CP violating scalar. Thus, if the data were to show that $BR(\phi \rightarrow \gamma Z)$ is larger than 60%, we would conclude that the dark matter is not a CP-even particle. Analogously, if $BR(\phi \rightarrow W^+W^-) + BR(\phi \rightarrow ZZ)$ were found to be larger than about 15%, we would conclude, from the right panel, that the dark matter is not a CP-odd particle. Notice that there are several configurations where the violation of CP could be claimed (the green points), but they all require two different branchings to be measured. For example, branching ratios of 30% and 40% respectively for $BR(\phi \rightarrow \gamma \gamma)$ and $BR(\phi \rightarrow \gamma Z)$ would indicate CP violation, according to the left panel. Similarly, if $BR(\phi \rightarrow \gamma \gamma)$ and $BR(\phi \rightarrow W^+W^-) + BR(\phi \rightarrow ZZ)$ were found to be respectively around 50% and 25%, we would conclude that the dark matter interactions violate CP. Such branchings, in fact, can only be reached with the CP violating points — see right panel.

Figure 2 shows an example of a $\gamma$-ray spectrum that, within our setup, can only be explained with CP violation. It corresponds to $M_{DM} = 165$ GeV, $BR(\phi \rightarrow \gamma \gamma) = 0.5$.

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2Since $M_{DM} = 165$ GeV in this case, this sum actually correspond to just $BR(\phi \rightarrow W^+W^-)$. 

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This spectrum can only be explained with CP violation. In this case, $M_{\text{DM}} = 165$ GeV, $\text{BR}(\phi \to \gamma\gamma) = 0.5$, $\text{BR}(\phi \to \gamma Z) = 0.25$, and $\text{BR}(\phi \to W^+W^-) = 0.25$. A 10% detector energy resolution was assumed to generate this figure. Notice that the two lines are clearly distinguishable. In this figure

$$x = E_{\gamma}/(M_{\text{DM}}/2).$$

In the figure one can clearly differentiate the two lines, from the $\gamma\gamma$ and $\gamma Z$ final states, and the continuum contribution, from $\gamma Z$ and $W^+W^-$ (we used the PPPC program [29] to get this contribution). For this figure, we adopted a 10% energy resolution, which is the Fermi-LAT value at 100 GeV. If the data were consistent with such a spectrum arising from dark matter decay, we would conclude that CP is violated by the dark matter interactions.

These correlations between the different final states turn out to strongly depend on the dark matter mass. For $M_{\text{DM}} < 2M_W$, only the decay modes $\gamma\gamma$ and $\gamma Z$ are kinematically allowed and no variation is observed with the CP properties of the dark matter particle. Both branchings simply vary between 0 and 1 satisfying $\text{BR}(\phi \to \gamma\gamma) + \text{BR}(\phi \to \gamma Z) = 1$. Hence, it is only for $M_{\text{DM}} > 2M_W$ that the branchings can in principle tell us something about the CP nature of the dark matter.

The left panel of figure 3 shows the correlation between $\text{BR}(\phi \to \gamma\gamma)$ and $\text{BR}(\phi \to \gamma Z)$ for a higher dark matter mass, $M_{\text{DM}} = 200$ GeV. From the figure we see that the two ellipses corresponding to the CP-even and the CP-odd points are now closer to each other, making more difficult to differentiate between these two possibilities.\footnote{In any case, the correlation with $ZZ$ and $W^+W^-$ provides additional information.} If, for instance, branching ratios of 10% and 15% were measured respectively for $\gamma\gamma$ and $\gamma Z$, a CP-odd particle would be excluded. Confirming CP violation, on the other hand, continues to be equally feasible for this higher mass. One example of a CP-violating point is $\text{BR}(\phi \to \gamma\gamma) = 40\%$ and $\text{BR}(\phi \to \gamma Z) = 25\%$.

At even higher masses it becomes impossible, even in principle, to distinguish between the CP-even and the CP-odd cases (see appendix), but it remains feasible to demonstrate CP violation. This situation is illustrated in the right panel of figure 3, which shows the correlation between the $\gamma\gamma$ and $\gamma Z$ branching ratios for $M_{\text{DM}} = 500$ GeV. In this case,
Figure 3. Correlations between the branching ratios into $\gamma\gamma$ and $\gamma Z$ for $M_{DM} = 200$ GeV (left panel) and $M_{DM} = 500$ GeV (right panel).

the CP-even and the CP-odd ellipses lie exactly on top of each other, meaning that the branchings have completely lost their discriminating power between these two possibilities. We still find, nonetheless, plenty of CP violating points (green) lying inside the ellipses, so CP violation could be established. The limiting factor at high masses is the capability of differentiating the two lines (a prerequisite to measure their branchings), which depends on the energy resolution of the detector. The GAMMA-400 $\gamma$-ray telescope [30], which aims at 1% energy resolution, would allow to distinguish the two lines up to dark matter masses of 400 GeV for annihilating dark matter [31], and slightly higher values for the case of decaying dark matter relevant to our proposal.

4 Discussion

We have shown that the correlations between the branching ratios into gamma-ray lines can be used to gain information on the CP properties of the dark matter particle. In practice, therefore, one needs to first extract the branchings from the observed signal — a non-trivial process due to the uncertainties associated with the halo profile and the background models. It is in principle feasible to do so, though, as we have learned from the analysis of the so-called Galactic Center Excess — see e.g. figure 6 of [32]. A detailed study of the precision with which the branchings into gamma-ray lines could be extracted from a future signal lies, however, beyond the scope of the present work.

Throughout this work we have assumed that the dark matter has spin zero and that it decays producing gamma-ray lines, so one might wonder what happens if that is not the case. If the dark matter has spin $1/2$, for example, there is a unique decay that produces monochromatic photons: $\gamma + \nu$ — see [27], which follows an effective operator approach analogous to the one we have discussed. As a result, it is not possible to examine the possible correlations between the different final states that give rise to a gamma-ray line, as we have done for the spin-zero case. Notice also that the observation of two-gamma
ray lines, such as those in figure 2, could be used to exclude the spin-1/2 case in a rather model-independent way. If, on the other hand, the gamma-ray lines are generated by dark matter annihilation rather than dark matter decay, the effective theory approach we relied on is no longer valid and it becomes more difficult to extract information about the CP-nature of the dark matter particle. For such scenarios, direct detection experiments may offer better prospects to determine the dark matter CP-properties — an idea that we are currently exploring.

5 Conclusion

We have shown that, under certain conditions, it is possible to determine whether the dark matter particle is a scalar (CP-even), a pseudoscalar (CP-odd), or if its interactions violate CP. The basic requirement to discriminate among these possibilities is the observation of γ-ray lines arising from the decay of a spin-zero dark matter particle. We argued that such a decay would most naturally be explained within the framework of effective field theory and demonstrated that, as a consequence of gauge invariance, there exists correlations between the branching ratios into γγ and γZ that depend on the mass and the CP nature of the dark matter particle. Thus, once these γ-ray lines are detected, one can check to see if their branchings are consistent with the predictions for a scalar, a pseudoscalar or a CP-violating scalar. In this way, it is possible to determine one of the fundamental properties of the dark matter particle: its CP nature.

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A Analytic expressions

The squared matrix elements for the two-body decays we consider can be obtained from the Lagrangian, equation (2.1), and are given by

\[ M_{\text{pl}}^2 |\mathcal{M} (\varphi \rightarrow \gamma \gamma) |^2 = 4 M_{\text{DM}}^4 \left[ (bc_W^2 + ds_W^2)^2 + (a c_W^2 + cs_W^2)^2 \right] \]  \hspace{1cm} (A.1)

\[ M_{\text{pl}}^2 |\mathcal{M} (\varphi \rightarrow \gamma Z) |^2 = 8 c_W^2 s_W^2 (M_{\text{DM}}^2 - M_Z^2)^2 \left[ (b - d)^2 + (a - c)^2 \right] \]  \hspace{1cm} (A.2)

\[ M_{\text{pl}}^2 |\mathcal{M} (\varphi \rightarrow W^+ W^-) |^2 = 8 \left[ M_{\text{DM}}^4 (c^2 + d^2) - 4 M_{\text{DM}}^2 M_W^2 (c^2 + d^2) + 6 c_W^4 M_W^2 \right] \]  \hspace{1cm} (A.3)

\[ M_{\text{pl}}^2 |\mathcal{M} (\varphi \rightarrow ZZ) |^2 = 4 \left[ M_{\text{DM}}^2 ((bs_W^2 + dc_W^2)^2 + (as_W^2 + cc_W^2)^2) - 4 M_{\text{DM}}^2 M_Z^2 ((bs_W^2 + dc_W^2)^2 + (as_W^2 + cc_W^2)^2) \right. \]  

\[ \left. + 6 M_Z^2 (as_W^2 + cc_W^2)^2 \right], \]  \hspace{1cm} (A.4)

where \( s_W^2 = \sin \theta_W \), \( c_W^2 = \cos \theta_W \), and \( M_{\text{DM}} \) denotes the mass of the dark matter particle. It is straightforward to compute from these expressions the decay width into the different channels and the corresponding branching ratios. From them, indirect detection limits on the couplings \( a, b, c, d \) can be derived — see e.g. [24].
For $M_{\text{DM}} \gg M_Z$, the expressions for the branching ratios get simplified to

\[
\text{BR}(\varphi \to \gamma \gamma) = \frac{(a^2 + b^2) c_W^4 + 2(ac + bd) s_W^2 c_W^2 + (c^2 + d^2) s_W^4}{a^2 + b^2 + 3(c^2 + d^2)} \tag{A.5}
\]

\[
\text{BR}(\varphi \to \gamma Z) = \frac{\sin^2(2\theta_W) \left( (a-c)^2 + (b-d)^2 \right)}{2(a^2 + b^2 + 3(c^2 + d^2))} \tag{A.6}
\]

\[
\text{BR}(\varphi \to W^+ W^-) = \frac{2(c^2 + d^2)}{a^2 + b^2 + 3(c^2 + d^2)} \tag{A.7}
\]

\[
\text{BR}(\varphi \to ZZ) = \frac{4 \cos(2\theta_W) \left( -a^2 - b^2 + c^2 + d^2 \right) + \cos(4\theta_W) \left( (a-c)^2 + (b-d)^2 \right)}{8(a^2 + b^2 + 3(c^2 + d^2))} + \frac{3a^2 + 2ac + 3b^2 + 2bd + 3c^2 + 3d^2}{8(a^2 + b^2 + 3(c^2 + d^2))}. \tag{A.8}
\]

From these results it can be checked that the parametric dependence of the branchings is exactly the same for the CP-even ($b = d = 0$) and CP-odd ($a = c = 0$) cases. Therefore, for $M_{\text{DM}} \gg M_Z$, the correlations between the different branching ratios cannot be used to distinguish between a scalar and a pseudoscalar dark matter particle. This analytic result is in agreement with the numerical results illustrated in the right panel of figure 3. Let us emphasize that it is still possible to confirm CP violation in this high mass limit.

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