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Extra U(1) as natural source of a monochromatic gamma ray line

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ABSTRACT: Extensions of the Standard Model with an extra $U'(1)$ abelian group generically generate terms coming from loops of heavy fermions, leading to three gauge boson couplings, in particular $Z'Z\gamma$. We show that WMAP data constrains the gauge coupling of the group g_D to values comparable with the electro-weak ones, rather independently of the mass of Z'. Moreover, the model predicts a monochromatic γ-ray line which can fit a 130 GeV signal at the FERMI telescope for natural values of the Chern-Simons terms and a dark matter mass around 144.5 GeV.

KEYWORDS: Beyond Standard Model, Cosmology of Theories beyond the SM, Gauge Symmetry

Contents

1   Introduction

One of the most important issues in particle physics phenomenology is the nature and properties of the dark matter in our universe. The observations made by the WMAP collaboration [1, 2] show that the matter content of the universe is dark, making up about 85 % of the total amount of matter. On the other hand, the XENON collaboration recently released its constraints on direct detection of Dark Matter [3, 4] excluding large regions of several extensions of the Standard Model. These constraints makes it plausible that dark matter sits in a different sector, communicating with our sector through new, weak enough interactions.

Neutral gauge sectors with an additional dark $U'(1)$ symmetry in addition to the Standard Model (SM) hypercharge $U(1)_Y$ and an associated Z' gauge boson are among the most natural extensions of the SM, and give the possibility that a dark matter candidate lies within this new gauge sector of the theory. Extra gauge symmetries are predicted in most Grand Unified Theories (GUTs) and appear systematically in string constructions. Larger groups than SU(5) or SO(10) allow the SM gauge group and $U(1)'$ to be embedded into bigger GUT groups. String theory and brane-world $U'(1)$s are special compared to GUT $U'(1)$'s; some of them are hidden, such that SM particles are uncharged under them. For a review of the phenomenology of the extra $U'(1)$s generated in such scenarios see e.g. [5]. In such a framework, the extra Z' gauge boson would act as a portal between the *dark* world (particles not charged under the SM gauge group) and the *visible* sector.

Several papers considered that the key of the portal could be the gauge invariant kinetic mixing $(\delta/2)F_Y^{\mu\nu}F'_{\mu\nu}$ [6–16]. One of the first models of dark matter from the hidden sector with a massive additional $U'(1)$, mixing with the SM hypercharge through both mass and kinetic mixings can be found in [17]. The Dark Matter (DM) candidate ψ_0 could be the lightest (and thus stable) particle of this secluded sector. Such a mixing has been justified in recent string constructions [18–22], but has also been studied within a model independent approach [23–33] or in a supersymmetric extension [34–37].

However, there exists another possibility for the Z' portal: the diagrams generated by

the Chern-Simons terms, usually related to the mechanism of gauge anomaly cancelation. It has been shown [38–40] that these vertices could generate a specific smoking-gun signal for dark matter searches: a monochromatic gamma ray line from the Galactic Center [41]. Moreover, the recent hint for such a line[1] [42–44] raises the hope and interests for such theoretical extensions of the Standard Model (see also [45–48] for very recent discussions about this subject). The purpose of the present note is to prove that such models naturally accomodate both the WMAP data on dark matter and the generation of a monochromatic gamma ray line from the Galactic Center.[2]

This note is organized as follows. After defining the model, we present the phenomenological consequences and study the parameter space which could respect WMAP and simultaneously explain a monochromatic gamma-ray line signal from the Galactic Center.

2   The model

Gauge invariance is a fundamental condition to ensure renormalizability and quantum consistency of any extension of the Standard Model. Triangle gauge anomalies cancelation can occur by a consistent field theory content or by cancelation of triangle loops by axionic couplings and Chern-Simons terms, via the string theory Green-Schwarz mechanism. At low-energy, remnants of the anomaly cancelation can lead to generalized Chern-Simon terms [59–61] containing new three gauge boson couplings. If one extend the Standard Model by an abelian gauge group $U'(1)$, at low-energy the particular Chern-Simons terms we are interested in is

$$\mathcal{L}_{\text{CS}} = \alpha_1 \ \epsilon^{\mu\nu\rho\sigma} Z'_\mu Z_\nu F^Y_{\rho\sigma} + \alpha_2 \ \epsilon^{\mu\nu\rho\sigma} Z'_\mu Z_\nu F'_{\rho\sigma} \,, \tag{2.1}$$

where CS stands for Chern-Simons, $F'_{\rho\sigma} = \partial_\rho Z'_\sigma - \partial_\sigma Z'_\rho$ and (α_1, α_2) are the coefficients (computable exactly once given the fermionic content of the model) generated by the triangle diagrams depicted in figure 1. In the loops are running heavy fermions charged under both $U(1)_Y$ and $U'(1)$ (when heavy fermion masses are SM gauge invariant such diagrams are still generated by higher dimensional operators [38, 62]). Notice that the CS terms (2.1) are invariant under electromagnetism[3] $U(1)_A$. The electroweak symmetry breaking then generates $Z'ZZ$, $Z'Z\gamma$ and $Z'Z'Z$ vertices.

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[1]At $3.3\,\sigma$ if one takes into account the look elsewhere effect, but currently unconfirmed by FERMI collaboration.

[2]Very few models can achieve such a signal as its production is one-loop suppressed. However, this monochromatic ray can be enhanced in other scenarios like SUSY ones [49–51], extra-dimension constructions [52], singlet DM [53], decaying DM [54], including a neutrino sector [55], effective DM models [56] or inert Higgs doublet DM [57]. Internal Bremsstrahlung [58] can also exhibit a spectrum similar to the one produced by the emission of a monochromatic γ-ray line.

[3]The broken SM symmetries and the $U(1)'$ are realized in a Stueckelberg phase, as explained in [38]. The CS terms can be written in the manifestly gauge invariant way $\frac{i}{M^2}\epsilon^{\mu\nu\rho\sigma} D_\mu\theta (D_\nu H^\dagger H - H^\dagger D_\nu H)(c_1 F^Y_{\rho\sigma} + c_2 F'_{\rho\sigma})$, where $D_\mu\theta = \partial_\mu\theta - g_X Z'_\mu$, where θ is the Stueckelberg axion absorbed by the Z' gauge boson. Moreover M is a mass scale related to the mass of the heavy fermions. After electroweak symmetry breaking, we recover (2.1) with $\alpha_i \sim c_i v^2/M^2$. We notice here that CS terms are also generic in string constructions, where their gauge non-invariance is compensated by axionic couplings and triangle loops of light fermions charged under the extra $U(1)'$. If light fermions are present, the computations of three gauge boson vertices are changed qualitatively, see e.g. [39, 40, 59–61], but we expect similar results to hold.
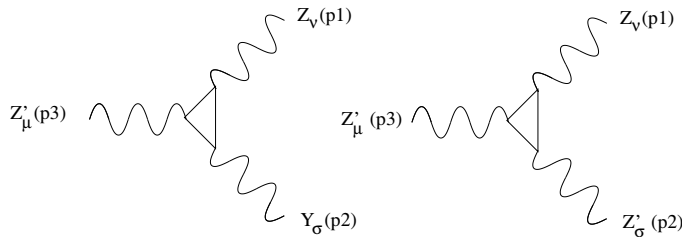
Figure 1. Triangle diagrams whose variation generate counter terms of the form eq. (2.1).
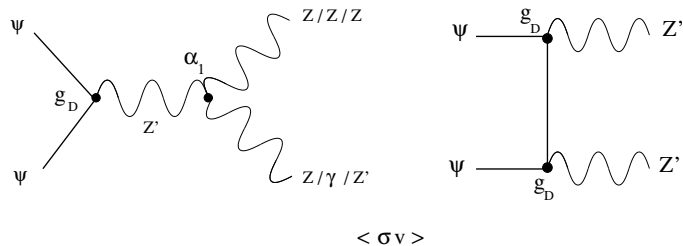
Figure 2. Feynmam diagrams contributing to the dark matter annihilation and $\gamma-$ray line observable by FERMI telescope.

From eq. (2.1) one can deduce the vertices and Feynman rules after the electroweak breaking:

$$\Gamma^{\mu\nu\sigma}_{Z'ZZ}(p_3; p_1, p_2) = 2\alpha_1 s_W \ \epsilon^{\mu\nu\rho\sigma}(p_1 - p_2)_\rho \,,$$
$$\Gamma^{\mu\nu\sigma}_{Z'Z\gamma}(p_3; p_1, p_2) = 2\alpha_1 c_W \ \epsilon^{\mu\nu\rho\sigma}(p_2)_\rho \,,$$
$$\Gamma^{\mu\nu\sigma}_{Z'ZZ'}(p_3; p_1, p_2) = 2\alpha_2 s_W \ \epsilon^{\mu\nu\rho\sigma}(p_2 - p_3)_\rho \,, \tag{2.2}$$

with the obvious notation $s_W = \sin\theta_W$ and $c_W = \cos\theta_W$.

If ψ is the lighter of the fermions charged under U'(1) (but not under the SM gauge group), coupling to Z' via the vertex

$$\Gamma^{Z'\bar{\psi}\psi}_\mu(p_3; p_1, p_2) = i\frac{g_D}{4}\gamma_\mu[(q_L + q_R) + (q_L - q_R)\gamma^5] \,, \tag{2.3}$$

where $q_L = q_R = 1$ in what follows, it can be considered to be a good dark matter candidate. The diagrams giving the annihilation rate contributing to the relic abundance are shown in figure 2. Depending on the kinematics and values of the couplings, each of the two diagrams can dominate. Nowadays, the dark matter candidate being mainly at rest, the process $\bar{\psi}\psi \to Z' \to Z\gamma$ can generate a monochromatic $\gamma-$ray line observable by the FERMI telescope. Depending on the mass of ψ, we describe in detail each possibility in the following section.

3 The monochromatic γ-ray line

Recently, it has been argued that the FERMI telescope did observe a monochromatic γ-ray line from the galactic center around a region $E_\gamma \simeq 130\,\text{GeV}$, with an annihilation

cross section $\langle\sigma v\rangle \simeq 2 \times 10^{-27} \text{cm}^3\text{s}^{-1}$ [42, 43], which would be a tantalizing smoking gun signal for new physics. Without discussing or anticipating the official analysis of the FERMI collaboration, we will try to check if such a clear signal can be produced by the CS terms generated in eq. (2.1). In what follows, we need to distinguish three different cases: $2m_\psi < M_{Z'} + M_Z$, $m_\psi < M_{Z'} < 2m_\psi - M_Z$ and $M_{Z'} < m_\psi$, for suitable values of the dark matter mass and couplings to fit the supposed γ-ray line. We will show how the first case is strongly disfavored by the astrophysical data and how the latter ones are compatible with very natural values for the parameters of the model. Even if all the discussion in what follows is qualitative, the numerical analysis has been done using a version of Micromegas [63–65], adapted to include the new features of the model.
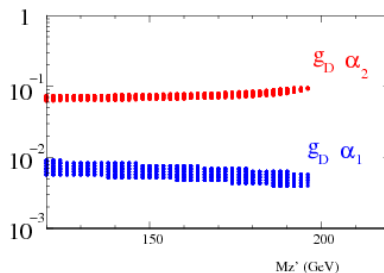
3.1 $M_{Z'} > 2m_\psi - M_Z$

In this case, the only annihilation process kinematically allowed is the $s-$channel exchange of a Z' (see the left figure 2). However, the two only final states being ZZ and $Z\gamma$, from the values of the couplings in eq. (2.2) one can easily deduce $\frac{\langle\sigma v\rangle_{ZZ}}{\langle\sigma v\rangle_{Z\gamma}} \simeq 0.3$ which means that the $Z\gamma$ final state is always the dominant one. If one wants to fulfill WMAP constraints for a thermal relic ($\langle\sigma v\rangle \simeq 3 \times 10^{-26} \text{cm}^3\text{s}^{-1}$), one should impose $\langle\sigma v\rangle_{Z\gamma} \simeq 2 \times 10^{-26} \text{cm}^3\text{s}^{-1}$. Such a huge cross section would have produced a visible monochromatic line, which is already apriori excluded by the FERMI collaboration. Therefore, the mass range $2m_\psi < M_{Z'} + M_Z$ is disfavored.

3.2 $m_\psi < M_{Z'} < 2m_\psi - M_Z$

In this case, the opening of a new channel $\bar{\psi}\psi \to Z' \to Z'Z$ allows the possibility to obtain a relic density obeying WMAP constraint *and* a monochromatic $\gamma-$ray flux observable by FERMI at the same time. In fact, the main difference with the case discussed in the previous subsection consists in the fact that now the contribution to the $\bar{\psi}\psi \to Z'Z$ process is proportional to the second Chern Simons coefficient of the eq. (2.1). Therefore, it is possible to decouple the two different processes, the annihilation cross section to fulfill WMAP, proportional to α_2, and the annihilation cross section giving a monochromatic signal, proportional to α_1.

The result is shown in figure 3, where we plotted the regions of the parameter space still allowed by WMAP and respecting $0.4 \times 10^{-27} \text{cm}^3\text{s}^{-1} < \langle\sigma v\rangle_{Z\gamma} < 1.09 \times 10^{-27} \text{cm}^3\text{s}^{-1}$ for a dark matter mass $m_\psi = 144.5 \text{ GeV}$. One can see that the dependence on the parameters can be expressed in terms of the products $g_D \times \alpha_i$. At the same time, as the WMAP constraints require a relatively larger cross section than the one for the monochromatic line, we require a ratio $\simeq 10$ between α_2 and α_1. Therefore, if one consider reasonable values for standard coupling of the Chern Simons terms, $\alpha_2 \simeq 10^{-2}$, from figure 3 one obtains $g_D \simeq 1$ and even stronger (non-perturbative) values for smaller values of α_2. This case is therefore compatible with the data, though a small hierarchy between α_1 and α_2 has to be assumed.

Figure 3. Combinations of Chern-Simon coefficients $g_D \times \alpha_1$ and $g_D \times \alpha_2$ respecting WMAP constraint and producing a monochromatic γ−ray line around $130\,\mathrm{GeV}$ with $\langle \sigma v \rangle_{Z\gamma} \simeq 2 \times 10^{-27}$ [42, 43] for $M_{Z'} \lesssim 2m_\psi - M_Z$ (case B, see the text for details).

3.3 $M_{Z'} < m_\psi$

In this region the main contribution to the dark matter annihilation process comes from the t-channel ψ exchange depicted in the right panel of figure 2. In this case, the relic density condition (independent on α_1 or α_2) is essentially decoupled from the s−channel diagram which produces the monochromatic line (figure 2 left). We recall again that it was because the *same* diagram was responsible for the relic abundance and the monochromatic line that for example the region $M_{Z'} > 2m_\psi - M_Z$ has been excluded in the discussion above. Moreover, interestingly in this case, differently from the scenario in which $m_\psi < M_{Z'} < 2m_\psi - M_Z$, our analysis becomes independent on the parameter α_2 as soon as $\alpha_2 \lesssim g_D$.

In more details, for a given monochromatic line (and so a given m_ψ), the WMAP condition fixes the coupling g_D: the cross-section for $\bar{\psi}\psi \to Z'Z'$ depends only weakly — through a phase space coefficient — on $M_{Z'}$. Then for a given value of the monochromatic annihilation cross section $\langle \sigma v \rangle_{Z\gamma}$, one can deduce the value of α_1 fitting the FERMI data. We made a scan on $(M_{Z'}, g_D, \alpha_1)$ and applied the 5σ constraint from WMAP and the annihilation cross section proposed by [42, 43] in the case of an Einasto profile. The result is presented in figure 4. In figure 5 we present an example of the gamma-ray spectrum obtained from the diagrams shown in figure 2, for a point in the parameter space respecting WMAP.[4]

There are three striking features in figure 4: first, there is a weak dependence on $M_{Z'}$; secondly, the value of g_D takes natural value for a U(1) coupling (we remind that $g_{EW} = 0.65$); and finally α_1 takes typical one-loop order values $\simeq 10^{-2}$, which are quite consistent with loop contributions generated by triangle diagrams of figure 1.

This range of values is understandable. Indeed, we know that an annihilation cross section $\langle \sigma v \rangle \simeq 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ leads to values of couplings of the order of the electroweak one for a WIMP mass of $100\,\mathrm{GeV}$. As only the dark coupling g_D appears in the annihilation channel (figure 2 right), one expect $g_D \simeq 0.6$ for a WIMP mass of $\sim 100\,\mathrm{GeV}$ independently on Z' mass (except around the threshold) as one can see in figure 4. Now, if one imposes that $\langle \sigma v \rangle_{Z\gamma} \simeq 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$, one can check semi-analitically that $\alpha_1 \simeq g_D/30$ which is effectively what we also observe in figure 4.

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[4]Micromegas was used for the calculation.
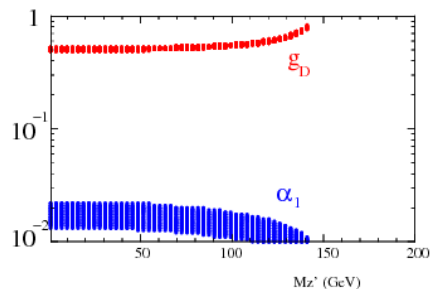
Figure 4. Dark coupling g_D and Chern-Simon coefficient α_1 respecting WMAP constraint and producing a monochromatic $\gamma-$ray line around $130 \, \text{GeV}$ with $\langle \sigma v \rangle_{Z\gamma} \simeq 2 \times 10^{-27}$ [42, 43] for $M_{Z'} \lesssim m_{\psi}$ (case C, see the text for details).
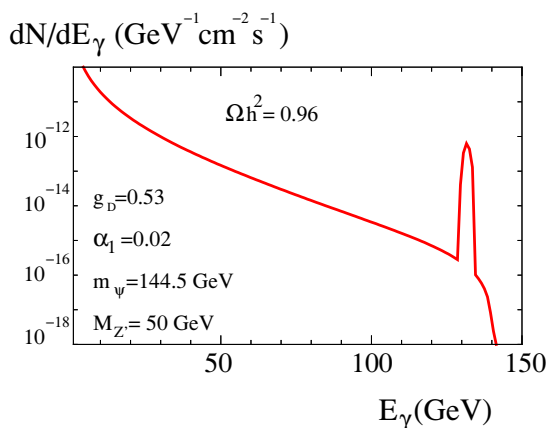
Figure 5. Example of spectrum observed from a cone within 0.1 radian from the Galactic Center, respecting WMAP and producing a monochromatic γ-ray line around $130 \, \text{GeV}$ with $\langle \sigma v \rangle_{Z\gamma} \simeq 2 \times 10^{-27}$.

It could be interesting to notice that in any of the cases discussed above, the direct detection rate is largely suppressed. Indeed, this rate can become important for a kinetic mixing around $\delta \simeq 10^{-3}$ [29–33] and could even explain DAMA/CoGENT excess with $\delta \simeq 10^{-2}$. However, in the model we are considering, the "portal" between the dark matter sector and the visible one does not go through this kinetic mixing, but through the tri-vectorial couplings generated in eq. (2.1). In this case, very low values of δ are still allowed, rendering the direct detection (through t-channel Z' exchange) very difficult to observe.

One can also remark that for $M_{Z'} \lesssim M_Z$, the $Z\gamma$ final state channel is kinematically closed. The main decay channel for the Z' is thus through the kinetic mixing with the Z. It is important to check that in this case the kinetic mixing should not be too small to disturb the Big Bang Nucleosynthesis (BBN) problem. A straightforward computation of the Z' lifetime leads to

$$\Gamma_{Z' \to q\bar{q}} \simeq \frac{e^2 \delta^2 \cos^2 \theta_W M_{Z'}}{108\pi} \tag{3.1}$$

$$\Rightarrow \tau_{Z'} \simeq 10^{-22} \frac{8\pi}{e^2 \delta^2 \cos^2 \theta_W} \left(\frac{M_{Z'}}{1 \, GeV} \right) \text{ (seconds)} .$$

One may deduce that for $\delta \gtrsim 10^{-11}$, the Z' decays before one minute and will not affect the BBN processes. Thus, the region $10^{-11} \lesssim \delta \lesssim 10^{-2}$ allows for a safely Z' decay from the BBN and electro-weak precision tests point of view. Moreover, notice that the natural one-loop contribution to the mixing, due to the diagrams induced by CS interaction terms, stays well inside that windows, for interesting (one-loop) values of the couplings α_i and reasonable assumptions[5] for the scale Λ where the theory is completed (for example, the mass M of the heavy fermions).

One should also notice that several constraints from the continuum photons should be taken into account, especially the ones coming from the dwarf galaxies measured by FERMI telescope[6] [66, 67]. Indeed, one have checked that the photons fluxes generated by the subsequent decays of the ZZ' final state (case B) or $Z'Z'$ (the ZZ final state giving weak fluxes, reduced by a factor $\simeq \sin^2 \theta_W$ compared to $Z\gamma$) does not exceed the constraints obtained by FERMI collaboration [66, 67].

4 Conclusion

We have discussed an extension of the Standard Model with an extra $U'(1)$ abelian group, where a three gauge boson couplings $Z'Z\gamma$ is generated from Chern-Simons terms. We studied the different scenarios allowed by this model, for different values of the mass parameters, under the hypothesis that the dark matter candidate is charged only under the extra abelian group. Depending on the ratio between the mass of the dark matter and the mass of the mediator Z', WMAP data constrains, more or less severely, the gauge coupling of the group g_D, but always allowing it to have a very natural value comparable with the usual electroweak ones, independently of the absolute value of the Z' mass. At the same time, for $M_{Z'} < 2m_\psi - M_Z$ and $M_{Z'} < m_\psi$ the model can provide a monochromatic $\gamma-$ray line which can fit a $130\,\mathrm{GeV}$ signal at FERMI telescope for a dark matter candidate mass $m_\psi = 144.5\,\mathrm{GeV}$, again for rather natural values of the Chern-Simons couplings.

Obviously, the model presented is intended to be an effective theory, where the unique effects of the beyond the standard model physics are encoded in the trilinear vector bosons couplings and the presence of a fermionic dark matter candidate. Nonetheless, already at this level it is possible to have a good estimate of the constraints that the new physics should satisfy in order to fit with this dark matter scenario. For example, the CS term in (2.1) contributes, at the loop level, to the mass of the Z gauge boson, which is experimentally known with an accuracy of $2 - 3\,\mathrm{MeV}$. An order of magnitude estimate gives $\delta M_Z^2 \sim (\alpha_i^2/16\pi^2)\Lambda^2$, where again Λ is an UV cutoff naturally of the order of the fermions generating the CS term. For couplings of order $\alpha_i \sim 10^{-2}$, we find $\Lambda \leq 500\,\mathrm{GeV}$, which is marginally consistent with limits on vector-like fermions in the Standard Model. It would be interesting to compare the constraints we obtained on α_1 and g_D from our combined WMAP/FERMI analysis with the constraints one could find with the LEP searches through the process $e^+e^- \to Z \to \gamma Z' \to \gamma\gamma Z$ which is a 2γ plus Z final state signature. However, such analysis is beyond the scope of the present paper.

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[5] Stronger constraints on Λ are discussed in the conclusion.

[6] We are grateful to the referee for having pointing us this issue.

Acknowledgments

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