A clear Dark Matter gamma ray line generated by the Green-Schwarz mechanism

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Abstract. We study the phenomenology of a $U_X(1)$ extension of the Standard Model where the SM particles are not charged under the new abelian group. The Green-Schwarz mechanism insures that the model is anomaly free. The erstwhile invisible dark gauge field $X$, even if produced with difficulty at the LHC has however a clear signature in gamma-ray telescopes. We investigate what BSM scale (which can be interpreted as a low-energy string scale) would be reachable by the FERMI/GLAST telescope after 5 years of running and show that a 2 TeV scale can be testable, which is highly competitive with the LHC.

Keywords: dark matter theory, gamma ray theory
1 Introduction

Recent experiments have shown that dark matter (DM) makes up about 25% of the Universe’s energy budget, but its nature is not yet understood [1–4]. A natural candidate is a class of weakly coupled massive particle (WIMP). Such a 100 GeV candidate would naturally give the right order of magnitude for the thermal relic abundance. One of the most studied extensions of the Standard Model (SM) is the Minimal Supersymmetric Model MSSM (mSUGRA in its local version) which extends the matter spectrum thanks to an extension of the space-time symmetries (see [5] and references therein). Alternative ideas have included attempts to study the dark matter consequences of the simplest gauge extension of the SM by adding a hidden sector charged under a new $U_X(1)$ symmetry [6, 7] and some specific signatures in gamma ray telescope were discussed. In [8] it was shown that the Stueckelberg $Z'$ extension of the SM leads to a viable milli-charged dark matter candidate, whereas the authors of [9] invoke a multiplet of states and an extra non-abelian light gauge boson to explain recent experimental anomalies. In several works [9, 10], kinematical mixing is necessary to couple the dark sector to the visible one, and many of these models have exotic matter, including non-vectorlike matter that couples to both SM and hidden sector gauge group, the lighter of which would be the DM candidate. However, none of these works focussed on the consequences of the anomalies induced by these kind of spectra on DM detection. Recently, some works have studied extensively the LHC prospect of such a construction [11–13] whereas one dimension 6 effective operator approach leads to specific astrophysical signals [14]. In this work, we show that, even if the SM particles are not charged under the extra $U_X(1)$, anomalies generated by the heavy fermionic spectrum can generate through the Green-Schwarz mechanism, $XZ\gamma$ effective couplings. This coupling induces a clear $\gamma$ ray line signal observable by GLAST at energy

$$E_\gamma = m_{DM} \left( 1 - \frac{M_Z^2}{4m_{DM}^2} \right),$$

where $m_{DM}$ is the WIMP mass. Line emission provides a feature that helps to discriminate against the background. The article is laid out as follows: we first review the motivations and construction of the effective vertex that couples the hidden sector $X$ gauge boson to the visible sector. After this, we compute the relic density generated by the lightest hidden fermion

1Which is our natural dark matter candidate whose stability can be ensure by the $U_X(1)$ symmetry.
\( \psi_{\text{DM}} \) and discuss the detection of the astrophysical signal and the related uncertainties, before concluding and comparing with LHC perspective and the predictions of different models.

2 Effective description of the model

It is well known that any extension of the SM which introduces chiral fermions with respect to gauge fields suffers from anomalies, a phenomenon of breaking of gauge symmetries of the classical theory at one-loop level. Anomalies are responsible for instance for a violation of unitarity and make a theory inconsistent [15, 16]. For this reason if any construction introduces a new fermionic sector to address the DM issue of the SM, it is vital to check the cancelation of anomalies and its consequences on the Lagrangian and couplings. In this letter, we concentrate on the Green-Schwarz mechanism which arises automatically in string theory settings. The idea is to add to the Lagrangian local gauge non-invariant terms in the effective action whose gauge variations cancel the anomalous triangle diagrams. There exist two kinds of term which can cancel the mixed \( U_X(1) \times G^A_{SM} \) anomalies, with \( U_X(1) \) being the hidden sector gauge group and \( G^A_{SM} \) one of the SM gauge group \( SU(3) \times SU(2) \times U_Y(1) \): the Chern Simons (CS) term which couples the \( G^A_{SM} \) to the \( U_X(1) \) gauge boson, and the Peccei-Quinn (PQ, or Wess-Zumino (WZ)) term which couples the \( G^A_{SM} \) gauge boson to an axion. In the effective action, these terms are sometimes called Generalized Chern-Simons (GCS) terms [17]. In order to describe the relevant structure, we can separate the effective Lagrangian into a sum of classically gauge variant and gauge invariant terms [11, 13, 17]:

\[
\begin{align*}
\mathcal{L}_{\text{inv}} &= -\frac{1}{4g^2} F^Y_{\mu\nu} F^Y_{\mu\nu} - \frac{1}{4g^2} F^X_{\mu\nu} F^X_{\mu\nu} - \frac{1}{2} (\partial_\mu a_X - M_X X_\mu)^2 - \bar{\psi} \gamma^\mu D_\mu \psi \\
\mathcal{L}_{\text{var}} &= C \frac{e}{24\pi^2} a_X \epsilon^{\mu\nu\rho\sigma} F^Y_{\mu\nu} F^Y_{\rho\sigma} + E \frac{e}{24\pi^2} \epsilon^{\mu\nu\rho\sigma} X_\mu Y_\nu F^Y_{\rho\sigma}.
\end{align*}
\]

(2.1)

The Stueckelberg axion \( a_X \) ensures the gauge invariance of the effective Lagrangian and \( g_X \) and \( F^X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu \) are the gauge coupling and field strength of \( U_X(1) \). The axion has a shift transformation under \( U_X(1) \)

\[
\delta X_\mu = \partial_\mu \alpha, \quad \delta a_X = \alpha M_X.
\]

(2.2)

Notice that our dark matter candidate is expected to be chiral with respect to the dark sector \( U_X(1) \), with a mass of the order of \( M_X \) because its mass should be generated by the spontaneous breaking of \( U_X(1) \). This differs considerably from the result obtained with a leptophylic dark sector [18] which considered vector-like dark matter with a Dirac mass term. A hierarchy between \( X \) and the lightest heavy fermion charged under \( U_X(1) \) (our natural dark matter candidate) would imply a hierarchy between hidden sector Yukawa and gauge couplings. The hidden fermionic sector being chiral, looking for the effects of mixed anomalous diagrams on DM phenomenology is not an ad-hoc assumption, but a necessity.

From eq. (2.1) and following [17], the triangle amplitude \([X_\mu(p_3) Y_\nu(p_1) Y_\rho(p_2)]\) can be decomposed according to

\[
\Gamma^{YY}_{\mu\nu\rho} = \left[ A_1 \epsilon_{\mu\nu\rho\sigma} p_2^\sigma + A_2 \epsilon_{\mu\nu\rho\sigma} p_1^\sigma \right]
\]

\footnote{We will consider \( U_X(1) \times U_Y^2(1) \) mixed anomalies throughout the paper to simplify the formulae, the generalization to \( U_X(1) \times SU^2(N) \) being straightforward.}

\[–2–\]
going particles are massless. It is straightforward to generalize the formulae in the case of

\[ \text{where each contribution to the amplitude is as shown in figure 1, and where } B_i \text{ satisfy} \]

\[
B_1(p_1, p_2) = -B_2(p_2, p_1) = -i \frac{g_X g^2}{8 \pi^2} Tr[Q_X Q_Y Q_Y] I_1
\]

\[
B_2(p_1, p_2) = -B_3(p_2, p_1) = -i \frac{g_X g^2}{8 \pi^2} Tr[Q_X Q_Y Q_Y] I_2
\]

with \( Q_i \) being the \( U_i(1) \) charges of the hidden fermions running in the loop, and \( I_i \) being finite computable integrals (see the appendix of [17] for details). Whereas \( A_i \) are UV cutoff dependent, following [11] the Chern-Simons coefficient can be reabsorbed if we define the coupling \( \tilde{A}_i = A_i + (-1)^{i+1} E \). The condition for the conservation of the 3 currents gives us 3 Ward identities

\[
\tilde{A}_1 = -p_1 \cdot p_2 B_1 - p_2^2 B_2
\]

\[
\tilde{A}_2 = -p_1 \cdot p_2 B_3 - p_2^2 B_3
\]

\[
C = \tilde{A}_1 - \tilde{A}_2
\]

We can now express our effective vertices in terms of finite integrals:

\[
\Gamma_{\mu \nu \rho}^{XZZ} = -2i \frac{\sin \theta_W g_X g^2}{8 \pi^2 M^2} Tr[Q_X Q_Y Q_Y] \left[ \tilde{I}_1 p_2^2 + \tilde{I}_2 p_1 p_2 \epsilon_{\mu \nu \rho \sigma} p_2^\sigma - [\tilde{I}_1 p_1 p_2 + \tilde{I}_2 p_1^2] \epsilon_{\mu \nu \rho \sigma} p_2^\sigma \right.
\]

\[
+ \tilde{I}_1 p_2 + \tilde{I}_2 p_1 \nu \epsilon_{\mu \nu \rho \sigma} p_2^\sigma p_1^\sigma - [\tilde{I}_2 p_1 \rho + \tilde{I}_1 p_2 \rho] \epsilon_{\mu \nu \sigma \tau} p_2^\sigma p_1^\tau
\]

\[
\left. + \frac{1}{p_3^2} [\tilde{I}_1 p_2^2 + \tilde{I}_2 p_1^2 + (\tilde{I}_1 + \tilde{I}_2) p_1 p_2 \epsilon_{\mu \nu \rho \sigma} p_2^\sigma p_1^\sigma] \right]
\]

\[
\Gamma_{\mu \nu \rho}^{XZZ} = -2 \left( \cos \theta_W / \sin \theta_W \right) \Gamma_{\mu \nu \rho}^{XZZ}
\]

where we defined \( \tilde{I}_i = M^2 I_i \), \( \tilde{I}_i \) being a dimensionless integral and \( M \) the \( U_X(1) \) breaking scale (typically the masses of the hidden fermions running in the loops). This scale can be thought of as coming from effective derivative couplings as was explicitly shown in [13, 14]. One might expect a \( \gamma \gamma \) decay channel as well, but this decay is forbidden when both outgoing particles are massless. It is straightforward to generalize the formulae in the case of

\[
\Gamma_{\mu \nu \rho}^{XZZ} = \frac{g_X}{4} \gamma^\mu \left( [q_X^R + q_X^L] + [q_X^R - q_X^L] \gamma^5 \right)
\]

\[
\Gamma_{\mu \nu \rho}^{XDM} = \frac{g_X}{4} \gamma^\mu \left( [q_X^R + q_X^L] + [q_X^R - q_X^L] \gamma^5 \right)
\]
extra fermions charged under $SU(2) \times U_Y(1) \times U_X(1)$. New couplings of the type $\Gamma^{XW+\tilde{W}^-}_{\mu\nu\rho}$ would be generated, but would not change the general conclusion of our study. Indeed, the annihilation channel $\psi_{DM}^2 \rightarrow X \rightarrow W^+W^-$ would give a spectrum quite similar to the one generated by the annihilation into $ZZ$ [14]. We made the analysis in a specific “next to minimal” $SU(2) \times U_Y(1) \times U_X(1)$ extension and found that generically the perspective of detection are even larger in such scenario than in the minimal $U_X(1)$ extension studied here. Our results are quite conservative in that sense.

Another interesting point is that, in order to generate dynamical masses from the $U_X(1)$ breaking, the hidden fermions (dark matter candidate included) should be chiral with respect to the parameter space that can be probed by the FERMI telescope.

Our results are quite conservative in that sense. Anomalies in QFT are of great interest for another reason: they could indirectly probe high energy physics and possibly even stringy effects. This is because anomalies can be thought of as both UV and IR effects. They are clearly visible in the limit of low-energy effective field theory which we expect to match to data, yet their UV character implies that the existence (and resolution) of these anomalies can often be tied to a stringy origin. This stringy origin makes the anomaly an interesting candidate for a stringy signature to be observed at colliders or in DM detection experiments. In particular, different string constructions do not have $U_X(1)$ couplings to SM fermions at tree level [19]. With this in mind, studying anomaly generated couplings and their consequences on the dark matter relic density is of fundamental importance. It is also important to mention that even if the spectrum is constructed so the model is anomaly free at the quantum level ($\text{Tr}[Q_XQ_YQ_Y] = 0$), triangle diagrams anomalies can contribute in a non trivial way to the $XYY$ vertices by higher dimensional operators (even dimension 4 for two extra $U(1)$) [13, 14, 16].

## 3 Dark matter phenomenology

### 3.1 Relic abundance

Since $\psi_{DM}$ is the lightest fermionic state that is charged under $U_X(1)$, the only allowed annihilation final states at tree level are $^3X$ or $Y$. Concerning the relic abundance of $\psi_{DM}$, we can easily deduce the different annihilation channels kinematically allowed (figure 2) from the effective coupling generated in Eqs (2.6–2.8). Using the symmetries and current conservation invoked above, one can parameterize the whole model by 3 physical parameters: $M_X$, $m_{DM}$ and $\Lambda_X = M \sqrt{8\pi^2/\text{Tr}[Q_XQ_YQ_Y]} g_X^2 g^2(I_2 - I_1)$. These low energy parameters would correspond to $g_X, Y_h$ (Yukawa of the lightest fermions in the hidden sector) and $\langle S \rangle$ (vev of the higgs breaking $U_X(1)$) in a dynamical version of the model. Our goal is to outline the parameter space that can be probed by the FERMI telescope.

We modified the micrOMEGAs code [20] in order to calculate the relic abundance of $\psi_{DM}$. It is easy to fulfill the WMAP 5σ bound [21] on $\Omega_{DM}$ for a wide range of the DM mass

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3We will suppose that the $X$ boson is lighter than the chiral matter in the hidden sector. As was emphasized in [11] this is not an unreasonable hypothesis as the mass of the most hidden sector matter will be dominated by higher symmetry breaking scales, and will thus be heavier than $X$. 

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Figure 2. Feynman diagrams contributing to the dark matter annihilation.

\[ \Lambda_X \text{ (TeV)} \]

Figure 3. Scan on the mass of X (in logarithmic scale) versus the effective scale \( \Lambda_X \). Colored lines represent the WMAP limits on the dark matter relic density for different values of the dark matter mass.

as shown in figure 3 in the \((M_X, \Lambda_X)\) plane for different values of the DM mass (100, 200 and 500 GeV). We can clearly see the s-channel resonance effect of \( \psi_{DM} \psi_{DM} \rightarrow X \rightarrow YY \) around the region \( M_X \simeq 2m_{DM} \). Within the band, the relic density respects WMAP constraints whereas below the pole, \( \Omega_{DM} < \Omega_{WMAP} \). We also notice a region where the relic density is below WMAP data on the left of the plot, where \( M_X \lesssim m_{DM} \). This region corresponds to the opening of the t-channel \( \psi_{DM} \psi_{DM} \rightarrow XX \) which depends on \( g_X \).\(^4\) For heavier X (\( M_X \gtrsim 1 \text{ TeV}, m_{DM} \gtrsim 500 \text{ GeV} \)) there still exist regions of the parameter space respecting WMAP. This occurs for higher values of \( \Lambda_X \) in order to decrease the \( XXYY \) coupling (proportional to \( 1/\Lambda_X \)) to compensate the increasing of the relic density proportional to \( m_{DM} \).

3.2 Indirect detection

The annihilation of WIMP into photons typically proceeds via a complicated set of processes with an upper cutoff at approximately the WIMP mass. A line due to the \( 2\gamma \) or \( Z\gamma \) pro-

\(^4\)It is important to notice here that \( g_X \) has been absorbed in the definition of \( \Lambda_X \) to avoid any explicit dependance on the coupling. For simplicity, we took \( g_X = 2 \) throughout the analysis.
duction channel could be observed as a feature in the astrophysical source spectrum \[22\]. In the most popular models, the branching ratio for the annihilation into lines is typically about \(10^{-3}\) or less. However, some models exhibit specific signatures as high energy rise due to final state radiation \[23, 24\]. Other dark matter candidates (like the Inert Higgs Dark Matter (IHDM) \[25, 26\], extra-dimensional chiral square theories \[27\] or neutralino in SUSY models \[28\]) can give strong monochromatic signals from \(\gamma\gamma\) or \(Z\gamma\) final states. However, except in \[14\], none of these models exhibit only one \(\gamma\) ray line but two or three. In the Green-Schwarz mechanism, \(\gamma\gamma\) final state is excluded by spin conservation, we are thus left with one monochromatic line, which would be a clear signature of the model. The spectrum of gamma-rays generated in dark matter annihilations and coming from a direction forming an angle \(\psi\) with respect to the galactic center is

\[
\Phi_{\gamma}(E_{\gamma}, \psi) = \sum_{i} \frac{dN_{\gamma}^i}{dE_{\gamma}} Br_i \langle \sigma v \rangle \frac{1}{8\pi m_{\chi}^2} \int_{\text{line of sight}} \rho^2 \, dl,
\]

where the discrete sum is over all dark matter annihilation channels, \(dN_{\gamma}^i/dE_{\gamma}\) is the differential gamma-ray yield, \(\langle \sigma v \rangle\) is the annihilation cross-section averaged over its velocity distribution, \(Br_i\) is the branching ratio of annihilation into final state “\(i\)”, and \(\rho\) is the dark matter density.

We know that a line due to the \(\gamma\gamma\) or \(Z\gamma\) channel could be observed in the astrophysical spectrum \[22\]. Such an observation is a "smoking gun" signal for WIMP DM as it is difficult to explain by a process other than WIMP annihilation or decay. Different models predicts different ratios for such processes. However, in SUSY or KK DM annihilation the \(\gamma\) line is typically loop suppressed as the main annihilation channel contributing to the thermal relic density dominates and gives a continuous \(\gamma\) spectrum. In some of the parameter space of the IHDM, for DM masses below the \(W\) mass, it has been shown in \[26\] that the two \(\gamma\) lines could be observed. A similar conclusion was found recently for the chiral square model \[27\]. The main reason is that in both models the \(Z\gamma\) and the \(\gamma\gamma\) are the only kinematically allowed annihilation channel, with a third line being generated by the KK final state in \[27\].

In our analysis we use diffuse-model simulated data from the centre annulus \((r \in [20^o, 35^o])\), excluding the region within \(15^o\) of the Galactic plane. It has recently been shown that it is possible in this case to minimize the contribution of the Galactic diffuse emission and could give a signal-to-noise ratio up to 12 times greater than at the Galactic Center (GC) \[34\]. A very interesting feature of excluding the GC in our analysis lies in the fact that our results are quite insensitive to the different dark matter profile (Einasto \[35\], NFW \[36\] or Moore \[37\]) as their contributions differ largely within the parsec region around the GC. In addition, we use the LAT line energy sensitivity for \(5\sigma\) detection calculated in \[33\]. The \(\gamma\)-ray spectrum is calculated using an adapted version\(^5\) of micrOMEGAs \[20\].

### 3.3 Results and discussion

As an illustrative point, we show in the left panel of figure 4 an example of spectrum from the centre annulus that could be observable by the FERMI telescope, generated by DM annihilation within the pole region respecting WMAP constraint\((m_{DM} = 258\text{ GeV and } M_X = 591\text{ GeV})\). We can clearly distinguish a \(\gamma\)-ray line centered around \(E_{\gamma} = m_{DM} \left(1 - \frac{M_X^2}{4m_{DM}^2}\right)\)

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\(^5\)The author wants to thank warmly G. Belanger and S. Pukhov for the precious help concerning the modification of the code.
Figure 4. Left: example of gamma-ray flux respecting WMAP constraint for a DM mass of 258 GeV. Right: monochromatic γ-ray fluxes generated by Green-Schwarz mechanism in comparison with expected 5σ and 95% CL sensitivity contours (5 years of FERMI operation) for the conventional background and unknown WIMP energy, for an effective scale \( \Lambda \) = 1.5 TeV.

generated by the s-channel resonance \( \psi_{\text{DM}}\psi_{\text{DM}} \rightarrow Z\gamma \) above the continuous flux produced by the annihilation process \( \psi_{\text{DM}}\psi_{\text{DM}} \rightarrow ZZ/Z\gamma \). We calculated the fluxes generated by the Green-Schwarz mechanism and compared it with the expected sensitivity of FERMI after 5 years of data-taking [29, 33] for 50 energy bins logarithmically distributed between 1 and 300 GeV (\( E_k = E_{\text{min}} e^{k(E_{\text{max}} - E_{\text{min}})} \)) and a gamma-ray width of 12% of \( E_\gamma \) corresponding to the energy resolution of FERMI. The results are presented in the right panel of figure 4. The Galactic diffuse model used in [33] is the GALPROP “conventional” model discussed in [30]. Indeed, the “optimized” model [31] seems to be disfavored by the non-confirmation of EGRET excess by the first FERMI released data [32]. We used the results obtained by the full detector Monte Carlo simulation and reconstruction framework detailed in [33].

We clearly see in the right panel of figure 4 that for \( \Lambda_X = 1.5 \) TeV, all the parameter space would be observable by FERMI at 95% CL. Indeed, the points that respect the WMAP constraints lie around the pole \( M_X \sim 2m_{\text{DM}} \) (see left panel of figure 5) where \( \sim 60\% \) of the annihilation rate is dominated by the \( Z\gamma \) final state. This proportion still holds for annihilating DM in the Galactic halo and gives a monochromatic line observable by FERMI. We also show what values of \( \Lambda_X \) are accessible by measurement of \( \gamma \)-ray for different values of DM masses (100, 200 and 300 GeV) in the right panel of figure 5, where all the points respect the WMAP relic abundance. We can see that for \( m_{\text{DM}} \gtrsim 100 \) GeV, \( \Lambda_X \gtrsim 1 \) TeV the model still gives a signal observable by FERMI at 95% CL. Obviously, for points lying away from the s-resonance we still have points which can respect WMAP constraint for lower values of \( \Lambda_X \). All these points (black circles in the right panel of figure 5) would be observable at 5σ after 5 running years of FERMI.

Using gamma-ray data from a variety of experiments, the authors of [38] have calculated conservative upper limits on the dark matter annihilation cross section to gamma ray lines over a wide range of masses. Combining results from COMPTEL, EGRET, HESS and INTEGRAL from different regions of the sky, and requiring the signal to be as large as the full measured background in an energy bin, they found that, for a background spectrum \( d\Phi/dE \sim 1/E^\alpha \), the upper limit to the cross section scales as \( (\sigma v)_{\text{limit}} \sim m_{\text{DM}}^{3-\alpha} \Delta(\ln E), \Delta(\ln E) \) being the logarithmic energy bin. We checked that this constraint is respected for each point of our parameter space. It is important to emphasize that in the annulus region
Figure 5. Left: scan on \((m_{\text{DM}}, M_X)\) plane and \(\Lambda_X = 1.5 \text{ TeV}\). Points respect WMAP constraints. Present experiments limits and FERMI sensitivity after 5 years of data taking are displayed. Right: monochromatic \(\gamma\)–ray fluxes generated by Green-Scharz mechanism in comparison with expected 5\(\sigma\) and 95\% CL sensitivity contours (5 years of FERMI operation) for the conventional background and unknown WIMP energy, for an effective scale \(\Lambda_X = 1.5 \text{ TeV}\).

our result are independent of the halo profile because the lower boundary of this region is 15\(^\circ\) from the Galactic Center, and the line of sight integral does not probe the cuspy region. Indeed, an isothermal-cored profile gives roughly the same result in this case.

We want to stress that because of the \(\sim 10\%\) energy resolution of the FERMI telescope for 68\% containment radius, the distinction of the two lines will be difficult for \(m_{\text{DM}} \gtrsim 170 \text{ GeV}\) \cite{noteref}. However, the distinction with other models with distinctive monochromatic \(\gamma\)–ray lines would still be possible.\(^6\) In the chiral square model, a third line from \(\gamma - KK\) excitation final state would be observable \cite{noteref}, whereas the \(\gamma\gamma\) and \(Z\gamma\) lines in the IHDM should be centered below \(m_Z\), and thus distinguishable by FERMI \cite{noteref}. The \(\gamma\)–spectrum generated from 3 body final states \cite{noteref} would be distinguishable from the \(Z - \gamma\) line, whereas lines generated by a neutralino DM should induce a large diffuse spectrum easily observable by FERMI. To complete the analysis, we also checked that a \(X - Z\) kinematic mixing respecting electroweak precision test \cite{noteref} does not affect the \(\gamma\)–ray line signal, as was already discussed in \cite{noteref}.

We may also calculate the WIMP-nuclei elastic scattering cross section \(\sigma_{\psi p}\) relevant for the direct detection of dark matter through its interaction with nuclei in a large detector. The points respecting WMAP constraint would give very low values for \(\sigma_{\psi p}\), below the sensitivity of any future experiments. This comes from the fact that the only diagrams contributing to the scattering is the t-channel \(X\) exchange. As \(X\) is not directly coupled to the quarks, but couples through intermediate virtual \(Z\)-exchange, the amplitude is highly loop suppressed as we found in preliminary results. See \cite{noteref} for a comparative study of other extensions of the SM.

### 3.4 Comparison with LHC

The Large Hadron Collider phenomenology of couplings generated by anomalous extra \(U_X(1)\) has recently been studied in the framework of the Green-Schwarz mechanism \cite{noteref} and higher dimensional operators \cite{noteref}. The former computed the production cross-section of the \(X\)

\(^6\)We would like to thank A. Morselli for drawing our attention to this fact.
boson from vector boson fusion at the LHC. It was shown that, for the mass range \((M_X \sim 500 - 1000 \text{GeV})\), LHC could detect the new physics through \(pp \rightarrow X \rightarrow ZZ \rightarrow 4l\) processes provided \(\Lambda_X \sim 100 - 150 \text{GeV}\). In the case of \(\gamma\)-ray detection we showed that in the same framework, the FERMI satellite will be much more efficient and will be able to probe a scale \(\Lambda_X \sim 100 - 4000 \text{GeV}\). The main reason is that the production of the \(X\) boson occurs through vector boson fusion and the \(qqX\) coupling is suppressed by a factor \(\sim g_X/\Lambda_X^2\), whereas in the case of DM annihilation, the \(\psi DM\psi DM X\) coupling is directly proportional to \(g_X\).

4 Discussion and conclusion

We have studied the phenomenology of a \(U_X(1)\) extension of the Standard Model where the SM particles are not charged under the new abelian group and where the Green-Schwarz mechanism ensures that the model is anomaly free. We showed that the dark gauge field \(X\), even though difficult to produce at the LHC has however a clear signature in gamma-ray telescopes. This \(U_X(1)\) extension has the unique feature that it generates a monochromatic \(\gamma\)-ray line from DM annihilation into \(Z\gamma\). This is quite different from other models which predicts two lines \([26]\) or three lines \([27]\), or one line radiated by fermions \([24]\). Such a signature would be a smoking gun signal for these types of constructions\(^7\) if the finite energy resolution of FERMI allows to separate the different lines \((m_{DM} \lesssim 170 \text{GeV} \text{ depending on the incident angle})\). We investigated the scales reachable by the FERMI/GLAST telescope after 5 years of running and showed the a scale \(\Lambda_X \sim 1.5 \text{ TeV}\) is easily observable. This scale can be interpreted as the string scale where the Green-Schwarz mechanism cancels the anomalies of the model. Alternatively, the absence of any signals would restrict the scale of such models to lie above \(\gtrsim 500 \text{GeV}\). Such sensitivity is highly competitive with the LHC.

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References

[1] F. Zwicky, Die Rotverschiebung von extragalaktischen Nebeln (in German), Helv. Phys. Acta 6 (1933) 110;
S. Smith, The mass of the virgo cluster, Astrophys. J. 83 (1936) 23.

[2] J.A. Tyson, G.P. Kochanski and I.P. Dell’Antonio, Detailed mass map of CL0024+1654 from strong lensing, Astrophys. J. 498 (1998) L107 [astro-ph/9801193] [SPIRES];
D. Clowe et al., A direct empirical proof of the existence of Dark Matter, Astrophys. J. 648 (2006) L109 [astro-ph/0608407] [SPIRES].

[3] WMAP collaboration, D.N. Spergel et al., Wilkinson Microwave Anisotropy Probe (WMAP) three year results: implications for cosmology, Astrophys. J. Suppl. 170 (2007) 377 [astro-ph/0603449] [SPIRES];

\(^7\)One should notice that in a specific context with a decaying gravitino DM, there can exist an observable \(\gamma\)-ray line well below \(M_{W^+}\) \([42]\).
WMAP collaboration, E. Komatsu et al., *Five-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: cosmological interpretation*, *Astrophys. J. Suppl.* **180** (2009) 330 [arXiv:0803.0547] [SPIRES].

[4] A. Borriello and P. Salucci, *The Dark Matter distribution in disk galaxies*, *Mon. Not. Roy. Astron. Soc.* **323** (2001) 285 [astro-ph/0001082] [SPIRES].

[5] G. Jungman, M. Kamionkowski and K. Griest, *Supersymmetric Dark Matter*, *Phys. Rept.* **267** (1996) 195 [hep-ph/9506380] [SPIRES]; C. Muñoz, *Dark matter detection in the light of recent experimental results*, *Int. J. Mod. Phys. A* **19** (2004) 3093 [hep-ph/0309346] [SPIRES]; G. Bertone, D. Hooper and J. Silk, *Particle Dark Matter: evidence, candidates and constraints*, *Phys. Rept.* **405** (2005) 279 [hep-ph/0404175] [SPIRES].

[6] See e.g. P. Langacker, *The physics of heavy $Z'$ gauge bosons*, arXiv:0801.1345 [SPIRES]; T.G. Rizzo, *$Z'$ phenomenology and the LHC*, hep-ph/0610104 [SPIRES].

[7] J.L. Feng, M. Kaplinghat, H. Tu and H.-B. Yu, *Hidden charged Dark Matter*, *JCAP* **07** (2009) 004 [arXiv:0905.3039] [SPIRES].

[8] K. Cheung and T.-C. Yuan, *Hidden fermion as milli-charged Dark Matter in Stueckelberg $Z'$ model*, *JHEP* **03** (2007) 120 [hep-ph/0701107] [SPIRES]; D. Feldman, Z. Liu and P. Nath, *The Stueckelberg $Z'$ extension with kinetic mixing and milli-charged Dark Matter from the hidden sector*, *Phys. Rev. D* **75** (2007) 115001 [hep-ph/0702123] [SPIRES]; PAMELA positron excess as a signal from the hidden sector, *Phys. Rev. D* **79** (2009) 063509 [arXiv:0810.5762] [SPIRES].

[9] N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer and N. Weiner, *A theory of Dark Matter*, *Phys. Rev. D* **79** (2009) 015014 [arXiv:0810.0713] [SPIRES].

[10] A. Ibarra, A. Ringwald, D. Tran and C. Weniger, *Cosmic rays from leptophilic Dark Matter decay via kinetic mixing*, *JCAP* **08** (2009) 017 [arXiv:0903.3625] [SPIRES]; S. Cassel, D.M. Ghilencea and G.G. Ross, *Electroweak and Dark Matter constraints on a $Z'$ in models with a hidden valley*, arXiv:0903.1118 [SPIRES]; S.A. Abel, M.D. Goodsell, J. Jaeckel, V.V. Khoze and A. Ringwald, *Kinetic mixing of the photon with hidden $U(1)s$ in string phenomenology*, *JHEP* **07** (2008) 124 [arXiv:0803.1449] [SPIRES]; G. Bélanger, A. Pukhov and G. Servant, *Dirac neutrino Dark Matter*, *JCAP* **01** (2008) 009 [arXiv:0706.0526] [SPIRES].

[11] J. Kumar, A. Rajaraman and J.D. Wells, *Probing the Green-Schwarz mechanism at the Large Hadron Collider*, *Phys. Rev. D* **77** (2008) 066011 [arXiv:0707.3488] [SPIRES].

[12] P. Anastasopoulos et al., *Minimal anomalous $U(1)'$ extension of the MSSM*, *Phys. Rev. D* **78** (2008) 085014 [arXiv:0804.1156] [SPIRES].

[13] I. Antoniadis, A. Boyarsky, S. Espahbodi, O. Ruchayskiy and J.D. Wells, *Anomaly driven signatures of new invisible physics at the Large Hadron Collider*, *Nucl. Phys. B* **824** (2010) 296 [arXiv:0901.0639] [SPIRES].

[14] E. Dudas, Y. Mambrini, S. Pokorski and A. Romagnoni, *In)visible $Z'$ and Dark Matter*, arXiv:0904.1745 [SPIRES].
T. Bringmann, L. Bergstrom and J. Edsjo, New gamma-ray contributions to supersymmetric Dark Matter annihilation, *JHEP* **01** (2008) 049 [arXiv:0710.3169] [SPIRES];
L. Bergstrom, T. Bringmann, M. Eriksson and M. Gustafsson, Gamma rays from Kaluza-Klein Dark Matter, *Phys. Rev. Lett.* **94** (2005) 131301 [astro-ph/0410359] [SPIRES];
A. Birkedal, K.T. Matchev, M. Perelstein and A. Spray, Robust gamma ray signature of WIMP Dark Matter, *hep-ph/0507194* [SPIRES];
J.F. Beacom, N.F. Bell and G. Bertone, Gamma-ray constraint on galactic positron production by MeV Dark Matter, *Phys. Rev. Lett.* **94** (2005) 171301 [astro-ph/0409403] [SPIRES].
[25] R. Barbieri, L.J. Hall, Y. Nomura and V.S. Rychkov, *Supersymmetry without a light Higgs boson*, Phys. Rev. D 75 (2007) 035007 [hep-ph/0607332] [SPIRES].

[26] M. Gustafsson, E. Lundstrom, L. Bergstrom and J. Edsjo, *Significant gamma lines from inert Higgs Dark Matter*, Phys. Rev. Lett. 99 (2007) 041301 [astro-ph/0703512] [SPIRES].

[27] G. Bertone, C.B. Jackson, G. Shaughnessy, T.M.P. Tait and A. Vallinotto, *The WIMP forest: indirect detection of a chiral square*, Phys. Rev. D 80 (2009) 023512 [arXiv:0904.1442] [SPIRES].

[28] L. Bergstrom, P. Ullio and J.H. Buckley, *Observability of gamma rays from Dark Matter neutralino annihilations in the Milky Way halo*, Astropart. Phys. 9 (1998) 137 [astro-ph/9712318] [SPIRES];
J. Hisano, S. Matsumoto, M.M. Nojiri and O. Saito, *Non-perturbative effect on Dark Matter annihilation and gamma ray signature from galactic center*, Phys. Rev. D 71 (2005) 063528 [hep-ph/0412403] [SPIRES];
T. Bringmann, L. Bergstrom and J. Edsjo, *New gamma-ray contributions to supersymmetric Dark Matter annihilation*, JHEP 01 (2008) 049 [arXiv:0710.3169] [SPIRES].

[29] N. Gehrels and P. Michelson, *GLAST: the next-generation high energy gamma-ray astronomy mission*, Astropart. Phys. 11 (1999) 277 [SPIRES].

[30] A.W. Strong, I.V. Moskalenko and O. Reimer, *Diffuse continuum gamma rays from the Galaxy*, Astrophys. J. 537 (2000) 763 [Erratum ibid. 541 (2000) 1109] [astro-ph/9811296] [SPIRES].

[31] E.A. Baltz et al., *Pre-launch estimates for GLAST sensitivity to Dark Matter annihilation signals*, JCAP 07 (2008) 013 [arXiv:0806.2911] [SPIRES].

[32] F. Stoehr, S.D.M. White, V. Springel, G. Torrens and N. Yoshida, *Dark Matter annihilation in the Milky Way’s halo*, Mon. Not. Roy. Astron. Soc. 345 (2003) 1313 [astro-ph/0307026] [SPIRES].

[33] J.F. Navarro, C.S. Frenk and S.D.M. White, *The structure of cold Dark Matter halos. I. Nonparametric construction of density profiles and comparison with parametric models*, Astron. J. 132 (2006) 2685 [astro-ph/0509417] [SPIRES].

[34] B. Moore et al., *Dark matter substructure within galactic halos*, Astrophys. J. 524 (1999) L19 [SPIRES].

[35] G.D. Mack, T.D. Jacques, J.F. Beacom, N.F. Bell and H. Yuksel, *Conservative constraints on Dark Matter annihilation into gamma rays*, Phys. Rev. D 78 (2008) 063542 [arXiv:0803.0157] [SPIRES].

[36] LAT collaboration, W.B. Atwood et al., *The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission*, Astrophys. J. 697 (2009) 1071 [arXiv:0902.1089] [SPIRES].
[40] J. Erler, P. Langacker, S. Munir and E.R. Pena, *Improved constraints on Z’ bosons from electroweak precision data*, *JHEP* **08** (2009) 017 [arXiv:0906.2435] [SPIRES].

[41] G. Bélanger, E. Nezri and A. Pukhov, *Discriminating Dark Matter candidates using direct detection*, *Phys. Rev. D* **79** (2009) 015008 [arXiv:0810.1362] [SPIRES].

[42] W. Buchmüller, L. Covi, K. Hamaguchi, A. Ibarra and T. Yanagida, *Gravitino Dark Matter in R-parity breaking vacua*, *JHEP* **03** (2007) 037 [hep-ph/0702184] [SPIRES];
G. Bertone, W. Buchmüller, L. Covi and A. Ibarra, *Gamma-rays from decaying Dark Matter*, *JCAP* **11** (2007) 003 [arXiv:0709.2299] [SPIRES];
K.-Y. Choi, D.E. Lopez-Fogliani, C. Muñoz and R.R. de Austri, *Gamma-ray detection from gravitino Dark Matter decay in the µSSM*, [arXiv:0906.3681] [SPIRES].