Isospin violating dark matter in Stückelberg portals with intersecting D-branes

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Abstract. Certain string theory constructions are representative of the so-called hidden sector scenarios in which the hidden particles interact with the Standard Model matter fields through the exchange of massive $Z'$ bosons. We show that such string motivated Stückelberg portals naturally lead to isospin violating interactions of DM particles with nuclei in direct detection experiments. We find that the ratios between the DM coupling to neutrons and protons for both, spin-independent ($f_n/f_p$) and spin-dependent ($a_n/a_p$) interactions, are generically different from $\pm 1$, and depend on the charges of the quarks under the extra $U(1)$ gauge groups. In order to find the experimentally allowed values of these ratios, we have incorporated constraints from searches for dijet and dilepton resonances at the LHC as well as LUX bounds on the elastic scattering of DM off nucleons. Our results highlight the importance of combining different search methods to shed light on this sort of scenarios.

1. Introduction

Hidden sector scenarios are among the best motivated theoretical frameworks for DM studies. In their minimal form, visible matter resides in a sector of the theory that hosts the Standard Model (SM) gauge and matter content (or simple extensions thereof), while DM resides in a hidden sector, with its own gauge and matter content, but that is otherwise neutral under the SM group. Due to the potential complexity of the hidden sector, DM candidates with many different characteristics can be accommodated, which makes this kind of theories very attractive. For instance, DM self-interactions, which are known to solve some of existing tensions between numerical simulations of collisionless cold DM and astrophysical observations, appear as a natural possibility in hidden sector scenarios due to the potential presence of gauge interactions between hidden particles.

Within such a framework, several mechanisms have been proposed to mediate non-gravitational interactions between the different sectors, usually referred to as portals. Among the best candidates, the Higgs portal [1] and the $U(1)$ extensions of the SM [2] provide an interesting possibility both from the theoretical and phenomenological points of view [3, 4, 5, 6]. In this talk we concentrate on the latter possibility, the so called $Z'$ portal, in which the hidden sector communicates with the SM by the exchange of one or several $Z'$ bosons.

The class of models considered here arise in D6-brane of type IIA string theory, where one generically obtains not $SU(3)_c \times SU(2) \times U(1)$, but rather $U(3) \times U(2) \times U(1)^p$ which contains several extra abelian factors (including the centers of $U(3)_c$ and $U(2)_L$).
Intuitively, each sector consists of several intersecting stacks of branes wrapping 3-cycles of a six-dimensional compactification space. The symmetry structure of this scenario can be represented schematically in the following form,

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{\nu} \times U(1)_{m} \times G_h$$

where the $U(1)_{\nu}$ are $n$ abelian gauge factors to which the visible matter fields $\Psi_v$ couple. All of the corresponding gauge bosons acquire a mass through the Stückelberg mechanism, except for a particular linear combination of them that corresponds to hypercharge and remains massless (in the phase of unbroken electroweak symmetry). $U(1)_{m}$ are $m$ abelian gauge factors (some of which could be massless) to which only hidden matter $\Psi_h$ couples, and $G_h$ represents the semi-simple part of the hidden gauge group.

2. The model

Regardless of the non-abelian sectors in the hidden and the visible (SM) stacks, the abelian part of the construction sketched in Eq. (1) can be, in general, described by the following effective Lagrangian [7, 8]

$$\mathcal{L} = -\frac{1}{4} \vec{F}_T \cdot \vec{F} - \frac{1}{2} \vec{A}_T \cdot M^2 \cdot \vec{A} + \sum_{\alpha} \overline{\psi}_\alpha \left( i\partial / + \vec{g}_\alpha^T \cdot \vec{A} \right) \psi_\alpha$$

where the vector $\vec{A}_T = (A_1 \ldots A_{n+m})$ represents all the $U(1)$ gauge bosons of the whole construction, with the corresponding field strength $\vec{F} = d\vec{A}$. Within this normalization, the gauge couplings are reabsorbed in the kinetic matrix $f$. The charge vectors $\vec{Q}_\alpha$ of a given matter field $\psi_\alpha$ will have non-zero entries only for one of the sectors (either visible or hidden), however the kinetic and mass matrices, $f$ and $M$, can have off-diagonal entries that mix both sectors. We will focus in the mixings induced by the mass matrix $M$ since, at tree level, the kinetic matrix is diagonal $f = \text{diag}(g^{-2}_1, \ldots, g^{-2}_N)$, with couplings determined by the volume of the cycles wrapped by the corresponding branes. Notice that loop corrections can generate off-diagonal terms that produce small kinetic mixings among different $U(1)$s, but in general those will be negligible with respect to the mixing induced by $M$ and thus not taken into account here.

The mass terms for the abelian gauge bosons $\vec{A}$ are generated by the Stückelberg mechanism. This is a consequence of the coupling of $\vec{A}$ to a set of pseudo-scalar periodic fields $\phi^i \sim \tilde{\phi}^i + 2\pi$, similar to the Higgs mechanism. The resulting matrix can be highly non-diagonal and have off-diagonal entries that mix hidden and visible sectors. This can happen with particular strength if the mixing is induced by the integer matrix of the axionic charges [9].

The Lagrangian given in Eq. (2) is now transformed into to a basis in which the gauge bosons have a canonical kinetic term and a diagonal mass matrix, and reads [9]

$$\mathcal{L} = -\frac{1}{4} F^\mu_\alpha \psi_\alpha + \frac{1}{2} \overline{\psi}_\alpha \left( i\partial / + \vec{g}_\alpha^T \cdot \vec{A} \right) \psi_\alpha$$

where coupling of a vector $A^\mu_\alpha$ to the matter field $\psi_\alpha$ is given by a linear combination of the original charges:

$$g^{(i)}_\alpha = \vec{Q}_\alpha^T \cdot \vec{v}(i)$$

The physical massive gauge bosons $A^\mu_\alpha$ will be hence a linear combination of both visible and hidden bosons and they will act as portals into hidden sectors.
the following couplings, visible sector particles [9]. The left and right handed (first and second family) of quarks have particles which will ultimately dictate the kind of interaction exists between the hidden and $h$ and $Z$ of the lightest impact on the phenomenology of the model.

from zero. These charges can be interpreted in terms of known global symmetries of $Z'$ induced by the lightest of the resulting physical $Z'$ bosons whose contribution to the DM interaction with SM particles will be dominant. Since we cannot know the explicit form of the mass matrix $M^2$ for generic string compactifications we will simply parametrise the couplings of the lightest $Z'$ boson to the matter fields $\psi_\alpha$ by a linear combination

$$g^{Z'}_\alpha = a Q_{\alpha A} + b Q_{\alpha B} + c Q_{\alpha C} + d Q_{\alpha D} + \sum_{i=1}^{m} h_i Q_{\alpha i}^{(h_i)}$$

where we have included the contributions from hidden $U(1)$ factors. The parameters $a, b, c, d$ and $h_i$ are precisely the entries of the vector $\vec{v}_\alpha^{Z'} = (a, b, c, d; h_1, \ldots)$ of Eq. (4). For massive $Z'$ bosons these are continuous parameters and as already stressed, they are all generically different from zero.

Finally, using all this information we can write down the couplings of the $Z'$ to the SM particles which will ultimately dictate the kind of interaction exists between the hidden and visible sector particles [9]. The left and right handed (first and second family) of quarks have the following couplings,

$$C^V_u = g^{Z'}_{u_L} + g^{Z'}_{u_R} = (b + c),$$

$$C^V_d = g^{Z'}_{d_L} + g^{Z'}_{d_R} = (b - c),$$

$$C^A_u = g^{Z'}_{u_L} - g^{Z'}_{u_R} = (2a + b - c),$$

$$C^A_d = g^{Z'}_{d_L} - g^{Z'}_{d_R} = (2a + b + c).$$

Similarly, for the third family of quarks and for leptons the vectorial and axial couplings can be straightforwardly written from Table 1. The structure of these couplings in terms of the parameters $a, b, c$ and $d$ highlights the aforementioned interpretation of the charges $Q_A$ and $Q_D$ in terms of baryon and lepton number since vectorial couplings do not depend on $a$ and $d$. Conversely, axial couplings do in fact depend on $a$ and $d$. This structure will have a remarkable impact on the phenomenology of the model.
4. Isospin violation in direct detection experiments

In the previous section we have shown that the different charges of the SM fermions under the $U(3)_A \times U(2)_B \times U(1)_C \times U(1)_D$ gauge group of the visible brane, added up to the mixing of the corresponding abelian bosons, produced very generic vector and axial couplings of these particles to the $Z'$ boson. Now we assume that the DM of the universe is fully accounted by a Dirac fermion generically denoted by $\psi$. This DM particle is living in the hidden sector and thus it will couple to each SM fermion through the $Z'$ in a different manner. As a consequence a different coupling strength of $\psi$ to protons and neutrons will rise, and hence, there will exist an isospin violation in both spin independent (SI) and spin dependent (SD) interactions.

Figure 1. Contours for the amount of isospin violation in the plane $a/c$ versus $b/c$. In the right panel we have superimposed the constraints from LUX and LHC.

In order to rearrange the results for both SI and SD interactions, in Figure 1 (left panel) we show the plane $a/c$ versus $b/c$. The dashed vertical lines represent some values of $f_n/f_p$, which are independent of $a/c$, as expected from the vectorial couplings. The solid lines denote some values for $a_n/a_p$, which indeed depend on $a/c$ since they come from the axial couplings. Interestingly, in the region depicted in the figure, where the values of $a$, $b$ and $c$ are in general of the same order, the DM interactions are isospin violating either in spin independent and spin dependent interactions. Besides, as it can be seen, very high values of the neutron component (with respect to the proton component) can be reached, although, the variation of either $f_n/f_p$ or $a_n/a_p$ is very abrupt in this region. This is important for direct detection experiments that use target materials in which the ratio between the neutron and proton contribution is significantly different than one. For instance, in Xe-based detectors such as LUX, the SD component is dominated by the neutron scatterings due to the dominance of the neutrons in the total spin of the $^{129}$Xe and $^{131}$Xe isotopes.

Although, as we have already seen, the amount of isospin violation in these class of models is very flexible, not all the values of the parameters $a$, $b$, $c$ and $d$ will be experimentally allowed. To show the impact of the experimental data on these models we select a specific benchmark point of the parameter space defined by the following quantities: $m_\psi = 500$ GeV, $m_{Z'} = 3$ TeV, $c = 0.1$, $d/c = 0.3$ and $b = 0.5$ (the latter is defined as the coupling of $\psi$ to the lightest $Z'$ as it can be seen in Eq. 5). In Figure 1 (right panel) we show the amount of isospin violation as in the left panel superimposing different constraints. The red area is excluded by the 2013 LUX analysis [12]. In blue we show the exclusion regions from the LHC searches for $e^+e^-$ (light blue) and $\mu^+\mu^-$ (blue) [13] and dijet resonances (darker blue) [9]. There is now only a tiny region allowed for this specific choice of parameters. In terms of isospin violation in the SI interactions, it corresponds to neutron dominance. For the SD interactions, the ratio $a_n/a_p$ is found to range between 1 and -10, approximately, and thus, it can be concluded that in general all interactions in direct detection experiments would be dominated by neutrons. The complementarity between direct DM searches and the LHC is remarkable. LUX rules out the values of $b/c$ stronger than
LHC in all cases, however, the LHC is able to constrain high values of $|a/c|$. Surprisingly, this complementarity is able to delimit the allowed portions of the parameter space so strongly that the we have obtained closed regions.

5. Conclusions
In this talk we have presented a model for DM with different possibilities in terms of phenomenology at direct detection experiments and the LHC which can be embedded into an ultraviolet completion model from the string theory point of view. We have shown that the couplings of the SM fermions to the lightest $Z'$ are very flexible. This fact is translated into a very generic amount of isospin violation in direct detection experiments. The use of different target materials in this kind of experiments would, in principle, disentangle the values of $f_n/f_p$ and $a_n/a_p$ and would reduce dramatically the allowed parameter space in these models. The complementarity between the LHC and direct detection experiments can be fully explored to constrain (discover) these scenarios. Most of the regions allowed by both kind of experiments encode a substantial coupling of DM to neutrons ($f_n/f_p > 1$). Finally, let us mention that this kind of models admit naturally more complex gauge structures and matter content in the hidden sector potentially opening the door to DM self-interactions and other interesting features that, hopefully, could be measured in the near future.

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