Physics Letters B 688 (2010) 212–215

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Signals of composite electroweak-neutral Dark Matter: LHC/direct detection interplay

Riccardo Barbieri [a,b], Slava Rychkov [c], Riccardo Torre [b,d,*]

[a] Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy
[b] INFN, Sezione di Pisa, Largo Fibonacci 3, I-56127 Pisa, Italy
[c] Laboratoire de Physique Théorique, École Normale Supérieure, and Faculté de Physique, Université Paris VI, France
[d] Università di Pisa, Dipartimento di Fisica, Largo Fibonacci 3, I-56127 Pisa, Italy

ARTICLE INFO

Article history:
Received 26 January 2010
Accepted 5 April 2010
Available online 9 April 2010
Editor: G.F. Giudice

Keywords:
Technicolor
Strong electroweak symmetry breaking
Dark matter
Techni-ω
LHC

ABSTRACT

In a strong-coupling picture of ElectroWeak Symmetry Breaking, a composite electroweak-neutral state in the TeV mass range, carrying a global (quasi-)conserved charge, makes a plausible Dark Matter (DM) candidate, with the ongoing direct DM searches being precisely sensitive to the expected signals. To exploit the crucial interplay between direct DM searches and the LHC, we consider a composite iso-singlet vector V, mixed with the hypercharge gauge field, as the essential mediator of the interaction between the DM particle and the nucleus. Based on a suitable effective chiral Lagrangian, we give the expected properties and production rates of V, showing its possible discovery at the maximal LHC energy with about 100 fb^{-1} of integrated luminosity.

1. Introduction and general properties

The possibility that Dark Matter (DM) be related, directly or indirectly, to the physics of ElectroWeak Symmetry Breaking (EWSB) deserves the highest consideration. Indeed this has been and is being extensively discussed both in weak-coupling and in strong-coupling scenarios of EWSB. The strong-coupling case is of interest to this Letter, without specific reference to any detailed model.[1]

We consider the case where the forces responsible for EWSB respect a global (quasi-)conserved charge X which enforces the (quasi-)stability of the lightest particle, Φ, with non-vanishing X. Φ is a candidate DM particle. Its mass, m_Φ, is in the TeV range, characteristic of the strong forces that may give rise to EWSB. This particle is made of constituents that feel the strong force and carry non-vanishing electroweak quantum numbers, but is itself electroweak-neutral. This is needed in order to suppress the tree-level coupling of Φ to the Z-boson, which would be in conflict with direct DM searches.

At face value, the cosmological relic abundance of the Φ-particles is too low to explain the observed DM energy density, Ω_{DM}, normalized as usual to the critical cosmological density. We have in mind the effect of two body processes, $\Phi\bar{\Phi} \leftrightarrow Q\bar{Q}$, where Q is any unstable particle lighter than Φ, also feeling the new strong force. For example, longitudinal W and Z bosons may play the role of Q. The associated thermally averaged cross section is far bigger than the needed $\langle\sigma v\rangle \approx 1$ pb, since

$$\langle\sigma v\rangle \approx \frac{\lambda^4}{4\pi m_\Phi^2} f\left(\frac{m_\Phi^2}{\Lambda^2}\right) \approx (10^6\ \text{pb})\left(\frac{\lambda}{4\pi}\right)^4\left(\frac{\text{TeV}}{m_\Phi}\right)^2 f\left(\frac{m_\Phi^2}{\Lambda^2}\right), \tag{1.1}$$

where $\lambda \approx 4\pi$ is a Naive Dimensional Analysis (NDA) estimate of the strong coupling λ, and the model-dependent function f of the ratio between the Φ-mass and the scale Λ characteristic of the new strong interaction is of order unity for $m_\Phi \approx \Lambda$.[2]

We are thus led to consider the case where the relic abundance of Φ-particles originates from a X–$\bar{X}$ asymmetry, analogous to the standard B–$\bar{B}$ asymmetry responsible for the dominance of matter over anti-matter in the present universe. An interesting aspect of this hypothesis is that one can try to relate $\Omega_X = \Omega_{DM}$ to the standard Ω_B by assuming that X, like B or L, are all broken by mixed

* Corresponding author at: INFN, Sezione di Pisa, Largo Fibonacci 3, I-56127 Pisa, Italy.
E-mail address: riccardo.torre@pi.infn.it (R. Torre).

[1] For a review of microscopic models of strong EWSB see [1].

[2] In Ref. [2], strongly interacting DM belonging to a non-EWSB hidden sector was considered, with a thermal freezout as the source of DM abundance. However, much higher DM masses up to 100 TeV were considered and smaller than NDA couplings were assumed.

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2010.04.010

electroweak anomalies. In this case, non-perturbative electroweak sphaleron interactions at a critical temperature $T^* \approx 100$–200 GeV may redistribute any original asymmetry, leading in particular today to [3]

$$\frac{\Omega_{DM}}{\Omega_B} = \mathcal{O}(10^2) x^{5/2} e^{-x}, \quad x = \frac{m_\Phi}{T^*}, \tag{1.2}$$

which can be about right, $\Omega_{DM}/\Omega_B \approx 5$, for m_Φ in the TeV range.

In this as in other cases of putative DM particles, the problem is to find experimental signals that would not only establish their existence but would allow a clear interpretation of their nature. To this end it is difficult to overestimate the interplay between direct DM searches and LHC experiments, as we are going to discuss.

2. Summary of direct detection signals

In absence of a detailed model, the possible signal in direct detection searches can be discussed by means of effective operators that mediate the interaction between Φ and the u, d-quarks or the photon [4]. The Φ-particle can be either a complex scalar or a Dirac fermion.

If Φ is a scalar, the dominant interactions are described by

$$O_1 = \frac{1}{\Lambda^2} (\Phi^* \overleftrightarrow{\partial_\mu} \Phi) \sum_{q=u,d} c_q (\bar{q} \gamma_\mu q),$$
$$O_2 = \frac{e c_2}{\Lambda^2} \partial_\mu F^{\mu\nu} (\Phi^* \overleftrightarrow{\partial_\mu} \Phi), \tag{2.1}$$

which for $c_q \approx c_2 \approx 1$, as expected from NDA, give comparable effects. Taking O_2 for concreteness, the non-relativistic cross section of Φ on a nucleus of charge Z and mass $m_N \ll m_\Phi$ is, up to form factor effects,

$$\sigma_2 = c_2^2 \frac{e^4 Z^2 m_N^2}{\pi \Lambda^4}. \tag{2.2}$$

For germanium target this corresponds to the per-nucleon cross section

$$\frac{\sigma_2}{A^4} \approx c_2^2 (2 \cdot 10^{-7}\ \text{pb}) \left(\frac{\text{TeV}}{\Lambda}\right)^4, \tag{2.3}$$

to be compared with the CDMS limit on the coherent spin-independent cross section [5]

$$\left.\frac{\sigma_{\text{SI}}}{A^4}\right|_{\text{exp}} \lesssim (2 \cdot 10^{-7}\ \text{pb}) \left(\frac{m_{DM}}{\text{TeV}}\right) \quad (m_{DM} \gg m_{\text{Ge}}), \tag{2.4}$$

i.e.

$$c_2 < \left(\frac{\Lambda}{\text{TeV}}\right)^2 \left(\frac{m_\Phi}{\text{TeV}}\right)^{1/2}. \tag{2.5}$$

For $c_2 \approx 1$, and $\Lambda \approx m_\Phi \approx 4\pi v \approx 3$ TeV, where $v \approx 250$ GeV is the electroweak VEV, the expected cross section (2.3) is about two orders of magnitude below the CDMS limit.

If instead Φ is a Dirac fermion, assuming parity invariance (up to anomalies) of the EWSB forces, the dominant operator is a magnetic moment interaction

$$O_M = \frac{i e c_M}{2\Lambda} (\bar{\Phi} \sigma_{\mu\nu} \Phi) F^{\mu\nu}. \tag{2.6}$$

In germanium, O_M gives rise to the dominant spin-independent cross section due to scattering on the current produced by the nuclear charge:

$$\frac{d\sigma_M}{dE} \approx c_M^2 \frac{e^4 Z^2}{4\pi \Lambda^2 E} \left(1 + \mathcal{O}(E/E_{\max})\right), \tag{2.7}$$

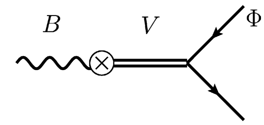

Fig. 1. The diagram which generates O_2 via the V–B mixing.

where E is the kinetic energy of the recoiling nucleus, ranging from the experimental threshold ~ 10 keV to $E_{\max} = 2v^2 m_N^2 = \mathcal{O}(100\ \text{keV})$. The spin-dependent cross section is subleading due to small nuclear spin of germanium and because of $E_{\max}/E$ enhancement present in (2.7) [4]. A suitable comparison of this cross section with the null CDMS result gives in this case

$$c_M < 10^{-1} \left(\frac{\Lambda}{\text{TeV}}\right) \left(\frac{m_\Phi}{\text{TeV}}\right)^{1/2}, \tag{2.8}$$

against the NDA estimate $c_M \approx 1$. Given the uncertainties of these estimates and of the value of the scale Λ itself, in no way this bound can be interpreted as ruling out a composite fermionic DM particle. Quite on the contrary, the message we draw is that a signal in direct DM searches could be around the corner. Yet we find it preferable, at least for reference, to stick in the following to the scalar case.

3. The DM-nucleus interaction mediated by a vector iso-singlet *V*

Suppose that a positive signal were indeed found in direct DM searches at the level indicated above, in fact not far from the present sensitivity. How would we know that the candidate DM particle is a composite Φ-like particle? As already mentioned, LHC should come into play here. However the detection at LHC of an electroweak-neutral particle of TeV mass that can only be pair produced may not be an easy task. For this reason, we turn the question into a different but related one. What could mediate the operators in Eq. (2.1) responsible in the first place for the direct DM signal? We argue that the most likely candidate for this role is a composite vector iso-singlet V, the analog of the ω-meson in QCD, strongly coupled to Φ and mixed with the elementary hypercharge gauge boson B_μ, via the diagram of Fig. 1.

We base our estimates on the following phenomenological Lagrangian

$$\mathcal{L} = \mathcal{L}_V + \mathcal{L}_{V\Phi} \tag{3.1}$$

where

$$\mathcal{L}_{V\Phi} = g_S V_\mu (\Phi^* \overleftrightarrow{\partial_\mu} \Phi), \quad g_S = 4\pi \frac{M_V}{\Lambda}, \tag{3.2}$$

and

$$\begin{aligned}\mathcal{L}_V = &-\frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} M_V^2 V_\mu^2 + \frac{g'}{4\pi} B_{\mu\nu} V_{\mu\nu} \\ &- \frac{i}{8\pi} \epsilon^{\mu\nu\rho\sigma} V_\mu \operatorname{tr}(u_\nu u_\rho u_\sigma) \\ &+ \frac{g}{4\pi} \epsilon^{\mu\nu\rho\sigma} V_\mu \operatorname{tr}(u_\nu \hat{W}_{\rho\sigma})\end{aligned} \tag{3.3}$$

in the standard notation for the electroweak chiral Lagrangian, i.e.

$$u_\mu = i u D_\mu U u^+ \approx i \partial_\mu U + g' B_\mu \frac{\sigma_3}{2} - g W_\mu^a \frac{\sigma_a}{2},$$
$$U = u^2 = e^{(i\sigma_a \pi^a / v)}, \tag{3.4}$$

$\hat{W}_{\mu\nu} = W_{\mu\nu}^a \sigma_a / 2$ is the usual field strength for the W boson, and the π-fields are the eaten up Goldstone bosons for EWSB. We assume that the couplings proportional to the epsilon tensor, relevant to the following section, are induced, analogously to the QCD