Kaluza–Klein Dark Matter from Deconstructed Universal Extra Dimensions

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Abstract. We consider Kaluza–Klein dark matter from deconstructed or latticized universal extra dimensions and study in this model the positron flux from Kaluza–Klein dark matter annihilation in the galactic halo.

INTRODUCTION

This talk is based on Ref. [1]. Today there is strong cosmological evidence for the presence of non-luminous dark matter [2]. Measurements indicate that the energy and matter in the Universe should be distributed such that approximately 73% is “dark energy”, 23% is “dark matter”, and around 4% is ordinary luminous matter. In recent years, an interesting alternative WIMP dark matter candidate, Kaluza–Klein dark matter (KKDM), has been intensively studied [3, 4]. The WIMP candidate is in this case the lightest Kaluza–Klein particle (LKP) in models with universal extra dimensions (UEDs), usually taken to be the first excited mode of the hypercharge gauge boson. It is stable due to the conservation of Kaluza–Klein (KK) parity and the detection prospects have been shown to be good [4]. Due to the close degeneracy of the KK spectrum, radiative corrections to KK masses could be crucial when determining the nature of the LKP. However, higher dimensional field theories are not renormalizable and unknown contributions from the UV-completion could therefore be essential. Recently, a possible UV-completion of higher dimensional gauge theories, known as deconstructed or latticized extra dimensions [5], was suggested. In these type of models, the higher-dimensional theory is interpreted as a non-linear sigma model, which can be completed in the ultraviolet, by for example a linear sigma model in 3+1 dimensions. In such a setting, one could calculate radiative corrections to KK masses [7]. We will address the possibility of KKDM in deconstructed universal extra dimensions. We will follow [8, 9], in particular [9], here extended to the leptonic sector. We will also discuss the prospects for indirect detection.

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2 E-mail adress: tomashal@kth.se
3 Usually, gravity is not included. For recent work on discretized gravity in 6D warped space, see [6].
4 We will not discuss radiative corrections.
THE MODEL

The fundamental model which we will consider is a linear sigma model in 3+1 dimensions with a product gauge group \( G = \prod_{j=0}^{3} SU(3)_j \times SU(2)_j \times U(1)_j \). The model contains fermions, gauge bosons as well as a set of link fields, \( Q_{j,j+1}, \Phi_{j,j+1}, \) and \( \phi_{j,j+1}, \) which transform in the bifundamental representation of adjacent \( SU(3), \ SU(2), \) and \( U(1) \) gauge groups, respectively. When the link fields acquire vacuum expectation values, \( \langle Q_{j,j+1} \rangle = v_3 1_3, \langle \Phi_{j,j+1} \rangle = v_2 1_2, \) and \( \langle \phi_{j,j+1} \rangle = v_1 / \sqrt{2} \), the product gauge group is broken down to the diagonal subgroup, which we identify as the standard model (SM) gauge group. At the same time, the kinetic terms for the link fields generates mass matrices for the gauge bosons, which after diagonalization yield for the \( U(1) \) gauge bosons the spectrum

\[
m_n^2 = \frac{g_\Phi^2 v_1^2 Y_\phi^2 \sin^2 \left( \frac{n \pi}{2(N+1)} \right)}{2(N+1)}
\]

and similarly for the \( SU(2) \) and \( SU(3) \) gauge bosons. This becomes, with the identification \( \pi g_\Phi v_1 Y_\phi / [2(N+1)] = 1/R \) and in the limit \( n \ll N \) indistinguishable from a usual linear KK spectrum \( m_n \approx n/R \). We identify the first excited mode \( \bar{A}_1 \) as the LKP and dark matter candidate.

We include a set of fermions \( L_j^\alpha, E_j^\alpha, \) for \( j = 0, 1, \ldots, N \) and \( \alpha = e, \mu, \tau \) (from now on flavor indices will be suppressed). Here \( L_j \) transforms as \( 2 \) under \( SU(2)_j \) and as a singlet under \( SU(2)_i, \) for \( i \neq j \). Furthermore, \( L_j \) is charged under \( U(1)_j \) as \( Y_d = -1 \). The field \( E_j \) is a singlet under all \( SU(2) \) groups and is charged under \( U(1)_j \) as \( Y_s = -2 \). Both \( L_j \) and \( E_j \) transform trivially under all \( SU(3) \) groups. In Ref. [2], the latticized action for the quark sector was considered. We construct analogously the action for leptons as \( S_{\text{fermion}} = S_d + S_s, \) where \( S_d \) refers to the part containing the \( SU(2) \) doublet fields and \( S_s \) contains the \( SU(2) \) singlet fields. The action \( S_d \) is obtained from a naive discretization of the continuum action augmented by a Wilson term, and is given by

\[
S_d = \int d^4x \left\{ \sum_{j=0}^{N} \bar{L}_j \gamma^\mu D_\mu L_j - \sum_{j=0}^{N} \left[ M_f \bar{L}_j \left( \frac{\Phi_{j,j+1}^1}{v_2} - \frac{\phi_{j,j+1}^3}{(v_1/\sqrt{2})^3} L_{j+1,R} - L_{j,R} \right) \right] + \text{h.c.} \right\},
\]

where \( M_f \) is a mass parameter which is used when matching to the continuum model. The expression for \( S_s \) is obtained similarly.

In order to obtain chiral zero modes, we take the doublet fields to satisfy \( L_{0R} = 0 \) and the singlet fields to satisfy \( E_{0L} = 0 \). When the link fields acquire universal VEVs, we obtain mass matrices for the fermion fields, which after diagonalization give for the left-handed doublet fields masses of the form as in Eq. (1), with \( g_\Phi^2 v_1^2 Y_\phi^2 \rightarrow 4M_f^2, \) where \( n = 0, 1, \ldots, N \) and for the right-handed doublets fields masses of the same form, but now \( n = 1, 2, \ldots, N \). Thus, there are no zeroth modes for the right-handed doublet fields. For the singlet fields the reverse situation holds. This reproduce the feature of chirality of the zero modes, as in the continuum theory. For \( n \ll N, \) we find a linear KK spectrum if we make the identification \( \pi M_f / (N+1) = 1/R \). It is straightforward to include also electroweak symmetry breaking masses. The Feynman rules for the fermion and gauge
boson interactions can be read off from the fermionic kinetic terms and the gauge boson field tensor terms, using the mode expansions. For the $L_{jL}$ and $E_{jR}$ interactions, as well as for the gauge boson self-interactions, KK-parity is conserved, even for a model with only few sites, which means that there are no decay channels in this sector. For the $L_{jR}$ and $E_{jL}$ sectors we find that for a few-site model KK parity is only approximately conserved in certain decay channels of the $\tilde{A}_1$ mode (the LKP) at loop level. These decay channels were not taken into account in [1]. However, for large $N$, KK parity becomes an arbitrarily good symmetry, also in these sectors of the model. The analysis for the quark sector is analogous. What is also needed in order to have the LKP as the dark matter candidate, are additional KK parity conserving interactions which violate KK number. These are in the continuum formulation generated at one-loop level from the orbifold compactification [10]. A similar analysis could be applied also to the deconstructed model, where deconstruction, in the sense of a UV-completion, could be useful when addressing contributions from UV-physics, which in the usual continuum model are not calculable. Here we will assume that such KK number violating interactions are present and leave the detailed analysis for future work.

INDIRECT DETECTION

In this section, we consider the positron flux from KKDM (i.e. $\tilde{A}_1$) annihilation in the galactic halo, for the lattice model described in the previous section. Here, as in [4] we only consider positrons from direct $e^+e^-$ production. The analysis will be similar to that of the continuum case, with the linear continuum KK mode spectrum replaced by the non-linear spectrum of the lattice model.

In calculating the differential positron flux, we have used the DARKSUSY package, see [11]. If the model in [1] is extended to include the KK parity violating one-loop decay channels mentioned earlier, then for a model with only few sites there may not be a viable dark matter candidate. A quantitative study is left for future work. For a large number of sites, KK parity becomes an arbitrarily good symmetry and the dark matter candidate is stable. In Fig[1] we present the differential positron flux as a function of the positron energy for an inverse radius of 450 GeV, for lattice models with $N = 1$ (i.e., two lattice sites), $N = 2$, $N = 3$, and the continuum model results. The parameter values are from Ref. [1].

The bounds on the mass of the first excited KK mode, coming from, for example, electroweak precision tests (EWPT), limits the prospects for indirect detection, with for example the PAMELA [12] and AMS-02 [13] experiments. It was shown in Ref [9] that the EWPT bounds are lowered for a lattice model, by as much as 10 %-25 %, for a few-site lattice model, the reason being the realization of a finite number of KK modes. Therefore, a lattice model could, in principle, improve the detection prospects for PAMELA and AMS-02.

The peak in the positron spectrum is as in the continuum model due to the monoenergetic positron source and is a characteristic signature of KKDM, distinct from the signal from neutralinos.
FIGURE 1. The differential positron flux (above background) for an inverse radius of 450 GeV as a function of positron energy, for direct $\ee$ production. Presented are latticized models with two lattice sites ($N = 1$, dotted curve), three lattice sites ($N = 2$, dashed curve) and four lattice sites ($N = 3$, dash-dotted curve) as well as the continuum model (solid curve). Given is also an estimated background flux (gray shaded). The unit of the ordinate is cm$^{-2}$s$^{-1}$sr$^{-1}$GeV$^{-2.5}$. Figure from [1].

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