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Universal extra dimensions : life with BLKTs

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Universal extra dimensions : life with BLKTs

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Abstract. In universal extra dimension (UED) models with one compactified extra dimension, a $\mathbf{Z}_2$ symmetry, termed KK-parity, ensures the stability of the lightest Kaluza-Klein particle (LKP) which could be a viable dark matter candidate. This symmetry leads to two fixed points in the extra space like direction. In non-minimal versions of UED boundary-localized kinetic terms (BLKT) of same strength at both fixed points induce a new $\mathbf{Z}_2$ symmetry which ensures the stability of LKP. The precision of the dark matter measurements severely correlates and restricts the BLKT parameters of gauge bosons and fermions. Furthermore, BLKT parameters of different strengths at the fixed would induce a non-consevation of KK-parity. We examine, in the presence of such terms, single production and decay of Kaluza-Klein excitations of the neutral electroweak gauge bosons in the context of LHC.

1. Introduction

After the discovery of Higgs boson at the LHC, much activity is now aimed to discover the physics which lies beyond the Standard Model. The evidence for such physics, though indirect, can be traced to the issue of naturalness of the Higgs mass, the observed masses and mixing of neutrinos, and the quest for a dark matter candidate. The energy scale for new physics remains unknown but there are several motivations which encourage us to expect that it may well be within the reach of the LHC. Models in which all the Standard Model fields propagate in one or more space like extra dimensions have many attractive features and they were proposed to overcome some of the shortcomings of the SM. In this article we will be discussing one such example, namely the UED model. In the next section we will briefly introduce the model and see that a nice feature of this model is the presence of a particle which could be a candidate for dark matter. Section 2, would be devoted to UED in the light of direct and indirect evidences from DM. This will be followed by a section devoted to the signatures of this model at the LHC. Finally we conclude in section 4.

2. Overview of UED with BLKT

Our concern here is a particularly interesting framework, called the UED scenario, characterized by a single flat extra dimension, compactified on an S^1/Z_2 orbifold (with radius of compactification, R)[1]. This extra space like dimension is accessed by all the SM particles. From a 4-dimensional viewpoint, every field in the SM will then have an infinite tower of Kaluza-Klein (KK) modes, each mode being identified by an integer, n, called the KK-number. The zero modes ($n = 0$) are identified as the corresponding SM states. The orbifolding is essential to ensure that fermion zero modes have a chiral representation. But it has other consequences too. The physical region along the extra direction y is now smaller $[0, \pi R]$ than the periodicity $[0, 2\pi R]$, so the KK number (n) is no longer conserved. What remains actually conserved is the even-ness and odd-ness of the KK states, ensured through the conservation of KK parity, defined by $(-1)^n$. Lorentz invariance along this direction is also lost due to compactification, and as a result the KK masses receive bulk and orbifold-induced radiative corrections [2]. As the theory under consideration lacks ultra-violet completeion, so instead of actually estimating the radiative correction (which is any case, logarithmically sensitive to the cut-off) one might consider kinetic and mass terms localized at the fixed points to parametrise these unknown corrections. We restrict ourselves to boundary-localized kinetic terms only [3, 4, 5, 6, 7, 8, 9]. Specifically we consider a five-dimensional theory with additional kinetic terms localized at the boundaries at $y = 0$ and $y = \pi R$. We call this incarnation as non-minimal UED (nmUED).

We illustrate the idea by considering free gauge fields $G^M(x, y)$ whose zero mode may be identified with photon for example.

The action with boundary kinetic terms can be written as

$$S = -\frac{1}{4}\int d^4x\, dy \left[F_{MN}F^{MN} + r_g^a\delta(y)F_{\mu\nu}F^{\mu\nu} + r_g^b\delta(y-\pi R)F_{\mu\nu}F^{\mu\nu}\right], \tag{1}$$

where $F_{MN} = (\partial_M G_N - \partial_N G_M)$ and $r_g^a,\ r_g^b$, the strengths of the boundary terms which are free parameters in our analysis along with the compactification radius R. It is straightforward to show that in the $G_4 = 0$ gauge, the gauge field has the KK-expansion

$$G_\mu(x, y) = \sum_{n=0}^{\infty} G_\mu^n(x)a^n(y). \tag{2}$$

where the functions $a^n(y)$ are of y-dependent part of the gauge fields. In this case the five-dimensional contributions to the KK-gauge field mass, m_n satisfy

$$(r_g^a r_g^b m_n^2 - 4)\ \tan(m_n\pi R) = 2(r_g^a + r_g^b)m_n\ . \tag{3}$$

In the above, $1/R$ is the inverse of the compactification radius of the extra space like dimension and this is the only (mass) dimensionfull parameters of our analysis.

KK-masses and wave functions of fermions and scalars are obtained by a similar method and for further details we refer [9].

3. nmUED via dark matter window

One of the burning issues of the SM is absence of a viable DM candidate . Although initially neutrinos or axions were hoped to be the required DM particle, from present day cosmological observations they are disfavored. The requirement of a dark matter candidate has been one of the important motivations to go beyond SM. UED, an alternate extension of the SM, also predicts its own dark matter candidate. Unlike the minimal UED, where $n = 1$ KK-excitation of $U(1)$ gauge field , B^1 is the LKP, in nmUED, one has the choice of LKPs from B^1, H^1 or W_3^1.

However in the following analysis we consider the 1st excited KK-level of hypercharge gauge boson B^1 is the relic particle, so the all other particles are unstable and ultimately decay to B^1 in association with SM particles. For extensive informations of relic density formulation in UED the reader is referred to [11, 12].

Evolution of number density n of relic (dark matter) particle in an expanding universe is governed by the Boltzmann equation,

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle (n^2 - n_{eq}^2), \tag{4}$$

here H is the Hubble parameter and n_{eq} the number density at thermal equilibrium.

$\langle \sigma_{eff} v \rangle$ ($\sim a_{eff}(x) + b_{eff}(x)\, v^2 + \mathcal{O}(v^4)$) is the thermally averaged relative velocity times the effective interaction cross section of B^1 with other particles in the spectra.

σ_{eff} can be defined as,

$$\sigma_{eff}(x) = \frac{1}{g_{eff}^2} \sum_{ij}^{N} \sigma_{ij} F_i F_j. \tag{5}$$

with

$$F_i(x) = g_i (1 + \Delta_i)^{3/2} \exp(-x\Delta_i) \text{ and } g_{eff}(x) = \sum_{i=1}^{N} F_i, \tag{6}$$

where

$$\Delta_i = \frac{m_i - m_0}{m_0} \text{ and } x = \frac{m_0}{T}. \tag{7}$$

g_i is the number of degrees of freedom for any particle which takes part in the annihilation or coannihilation process, σ_{ij} is the corresponding cross section and m_0 is the mass of relic particle.

The approximate formula for the relic density,

$$\Omega h^2 \approx \frac{1.04 \times 10^9/1\text{GeV}}{M_{Pl}} \frac{x_F}{\sqrt{g_*(x_F)}} \frac{1}{I_a + 3I_b/x_F}, \tag{8}$$

M_{Pl} is the Planck mass and $I_a = x_F \int_{x_F}^{\infty} a_{eff}(x) x^{-2} dx$, $I_b = 2x_F^2 \int_{x_F}^{\infty} b_{eff}(x) x^{-3} dx$,

here x_F is the freeze-out temperature and $g_*(x_F)$ accounts for the relativistic degrees of freedom at the freeze-out temperature.

The strengths of BLKTs have been be chosen such that B^1 is always the LKP [13]. We assume BLKTs for other particles in such a manner that coannihilation of only left-handed lepton doublet fermions are relevant. Coannihilation becomes less important as the mass splitting in the $n = 1$ level increase.

In fig.1, we present the main results of this section. For several choices of fermion BLKT parameters, Ωh^2 has been plotted as a function of $1/R$. The blue (shaded) band represents the 1σ allowed range of relic density measured from PLANCK [14].

Range BLKT parameters those are allowed from the measured relic-density can be read off from the plots by looking at the intersection of the lines with the blue band in fig.1. Unlike UED, the allowed range of R^{-1} depends on R_f in this non-minimal version of the model. As R_f moves away from R_B the splitting, Δ_f , increases and coannihilation becomes less important.

4. Probing nmUED via KK-parity violation at the LHC

In this section we will be interested in a special situation where the strength of the BLKT parameters at the two fixed points are not the same. This results into violation of KK-parity which in turn is manifested by non-vanishing couplings among $n = 0$ KK-states with $n = 1$ KK-states. In particular we will be interested in single production of B^1 and W_3^1 in proton proton collision at the LHC, followed by the decay of B^1 into a pair of SM charged leptons. Both the production and decay are driven by couplings which do not respect KK-parity.

Relevant couplings can be easily obtained in [9]. In fig.2 such KK-parity violating couplings between B^1 or W_3^1 to a pair of SM ($n = 0$ KK-mode) fermions has been plotted with ΔR (the difference between the BLKT parameters of the gauge bosons at two fixed points). As expected, these couplings grow with ΔR, the measure of KK=parity violation.

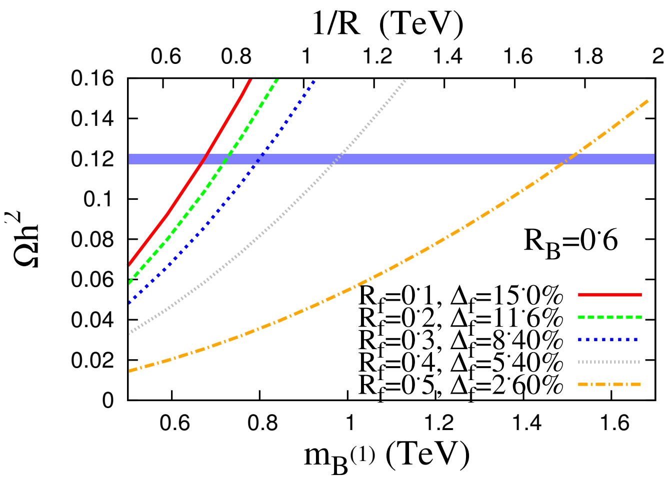

Figure 1. Variation of Ωh^2 with relic particle mass. Curves for different choices of the fermion BLKT parameter R_f are shown and the corresponding Δ_f indicated. The narrow horizontal blue band corresponds to the 1σ allowed range of relic particle density from Planck data. The allowed $1/R$ can be read off from the intersections of the curves with the allowed band. This panels correspond to a fixed value of R_B.

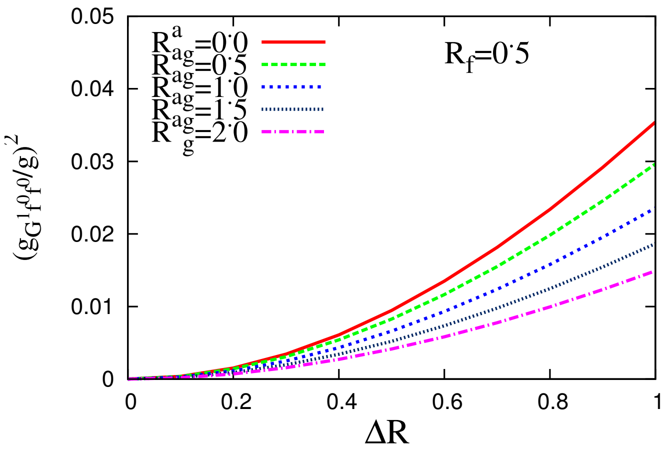

Figure 2. Variation of the square of the KK-parity violating coupling (between $B^1 or W^1_3$ and a pair of zero-mode fermions) with ΔR for several choices of R^a_g. This panels correspond to a fixed value of R_f.

We are now in a position to discuss some phenomenological signals of nmUED. In the following we will restrict our discussion only to the prospects at the LHC. Though for B^1 and W^1_3 we choose different BLKT strengths we keep ΔR to be the same for both B^1 and W^1_3. At the LHC we are interested to investigate the resonant production of the $n = 1$ KK-excitations of the neutral electroweak gauge bosons, via the process $pp(q\bar{q}) \to G^1$ followed by $G^1 \to l^+l^-$ where G^1 is either of B^1 and W^1_3 and l could be either $e^\pm$ or $\mu^\pm$. If in future such a signature is observed at the LHC, then it would be a good channel for the determination of such KK-parity violating couplings.

An analytic expression for the production cross section in proton proton collisions can be written in a compact form :

$$\sigma(pp \to G^1 + X) = \frac{4\pi^2}{3m^3_{g^{(1)}}} \sum_i \Gamma(G^1 \to q_i\bar{q}_i) \int_\tau^1 \frac{dx}{x} \left[f_{\frac{q_i}{p}}(x, m^2_{g^{(1)}}) f_{\frac{\bar{q}_i}{p}}(\tau/x, m^2_{g^{(1)}}) + q_i \leftrightarrow \bar{q}_i \right] \tag{9}$$

Here, q_i and $\bar{q}_i$ stand for a generic quark and the corresponding antiquark of the i-th flavour respectively. $\Gamma(G^1 \to q_i\bar{q}_i)$ represents the decay width of G^1 into a quark and antiquark pair of the ith flavour. $\tau \equiv m^2_{g^{(1)}}/S_{PP}$, where $\sqrt{S_{PP}}$ is the proton proton centre of momentum energy. The fs are quark or antiquark distribution functions within a proton.

In case of of B^1 production $\Gamma = \left[(g^2_{G^1 q\bar{q}}/32\pi) \times [(Y^q_L)^2 + (Y^q_R)^2]\right] m_{B^{(1)}}$ (with Y^q_L and Y^q_R being the weak hyper-charges for the left- and right-chiral quarks), while for W^1_3 one has $\Gamma = \left[g^2_{G^1 q\bar{q}}/128\pi\right] m_{W_3^{(1)}}$, $g_{G^1 q\bar{q}}$ is the KK-parity violating coupling among SM quarks. To obtain the numerical values of the cross-sections, we use a parton level Monte Carlo code with parton distribution functions as parametrized in CTEQ6L [15]. We take the pp centre of momentum energy to be 8 TeV. Renormalisation (for α_s) and factorisation scales (in the parton distributions) are set at $m_{g^{(1)}}$.

In fig.3, the main results of our analysis has been presented in the context of 8 TeV run of the LHC. As the above signal is practically background free, 40 signal event can be assumed to be a benchmark for discovery. In the figure, contours of 40 signal events have been plotted in the $\Delta R - (R^a_B - R^a_W)$ plane. If no such signal would be seen at the LHC, parameter space above a particular line could be excluded.

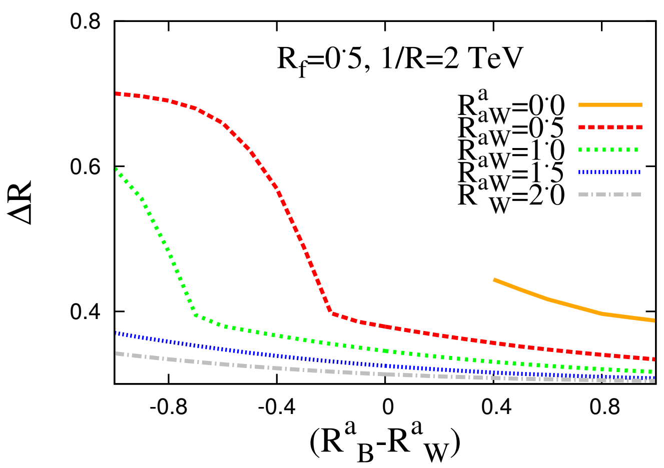

Figure 3. Iso-event curves (40 signal events with 20 fb^{-1} data at the LHC running at 8 TeV) for combined W^1_3 and B^1 signals in the $\Delta R - (R^a_B - R^a_W)$ plane for several choices of R^a_W. This panel corresponds to specific values of R_f and R^{-1} while ΔR_g is taken to be the same for W^1_3 and B^1. The regions below the curves correspond to less than 20 events for the chosen R_f and R^a_W. R^{-1} is taken as 2 TeV for this panel.

5. Summary

In summary, we have investigated phenomenology of a model with gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$, in which all the Standard Model fields propagate in $1+4$ dimensional manifold.

The extra space like dimension is compactified on an orbifold with two fixed points. Effective 4-dimensional theory thus consists of towers of excitation of SM fields. An imposed Z_2 symmetry results into presence of a weakly interacting stable massive particle in the spectra. Radiative corrections to the masses and the couplings in this theory are log sensitive to the cut-off thus having certain amount of arbitrariness. In an incarnation of this model, log divergent radiative corrections are parametrised by adding all possible kinetic terms involving the fields at the orbifold fixed poiints. We have reported the results of relic density calculation in the framework of this model. Furthermore, taking boundary kinetic terms with unequal strengths would result into some dramatic signatures of this model at colliders. In particular we have investigated production and decay of lightest KK-excitation of electroweak gauge bosons at the LHC. Observation/non-observation of such signals at the LHC in near future would definitely help us to discover/exclude nmUED.

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