Constraining nmUED from Dark Matter Analysis

Ujjal Kumar Dey
in collaboration with
Anindya Datta, Avirup Shaw and Amitava Raychaudhuri
arXiv: 1305.4507

Harish-Chandra Research Institute

Higgs and BSM Physics at the LHC
ICTP

June 24, 2013

Outline

- non-minimal Universal Extra Dimension
- Mass spectrum and KK-parity
- Relic density calculation
- Direct detection prospects
- Summary

non-minimal Universal Extra Dimension

- One extra spatial dimension, y, compactified on an $S^1/\mathbb{Z}_2$ orbifold.
- Two fixed points, $y = 0$ and $y = \pi R$, called boundaries of the orbifold.
- Orbifolding breaks the translational invariance in the fifth direction, thus leading to non-conservation of KK-number, leaving KK-parity intact.
- No boundary localised terms (BLT) in the minimal case.
- Relaxing the assumption of non-vanishing BLTs imply nmUED.
- Here the BLTs of fermions and gauge bosons are taken and the parameter space has been constrained from the dark matter relic density and direct detection observations.

Mass spectrum in nmUED

- For example, the 5D gauge boson action with boundary localised kinetic terms(BLKTs),

$$S = -\frac{1}{4}\int d^5x\left[F_{MN}F^{MN} + \{r^a\delta(y) + r^b\delta(y-\pi R)\}F_{\mu\nu}F^{\mu\nu}\right]$$

- Expansion of the gauge field,

$$A_\mu(x,y) = \sum_{n=0}^{\infty} A_\mu^{(n)}(x)a_n(y), \quad A_5(x,y) = \sum_{n=0}^{\infty} A_5^{(n)}(x)b_n(y)$$

- $a_n(y)$ and $b_n(y)$ can be determined from the boundary conditions.
- For example, the function $a_n(y)$ satisfy,

$$\partial_y^2 a_n(y) + \left[1 + r^a\delta(y) + r^b\delta(y-\pi R)\right] m_n^2 a_n(y) = 0$$

KK parity conservation

- $a_n(y)$ can be solved using appropriate boundary conditions,

$$a_n(y) = N_n \left[\cos(m_n y) - \frac{r_b m_n}{2} \sin(m_n y)\right]$$

- The masses m_n are solutions of,

$$\tan\left[m_n \pi R\right] = \frac{2(r^a + r^b)m_n}{r^a r^b m_n^2 - 4}$$

- Similar type of equations can be obtained for fermions, starting from the fermion action.
- It can be shown that non-zero KK-parity violating coupling exists if $r^a \neq r^b$.
- KK-parity is restored if $r^a = r^b$ and then we recover LKP, i.e., $\gamma^{(1)}$, which can safely be assumed to be $B^{(1)}$, as the dark matter candidate.

Masses and couplings in nmUED

- The mass spectrum in nmUED is determined by the BLKT parameters, r's.

$$r m_{(n)} = \begin{cases} -2\tan\left(\frac{m_{(n)}\pi R}{2}\right) & \text{for } n \text{ even} \\ 2\cot\left(\frac{m_{(n)}\pi R}{2}\right) & \text{for } n \text{ odd} \end{cases}$$

- The couplings will also be modified from the minimal case due to the presence of the BLKT parameters.
- The modifications in the couplings are incorporated in terms of overlap integrals of the mode functions, e.g.,

$$\begin{aligned} g^{(4)}_{\Phi_1\Phi_2\ldots\Phi_k} &= g^{(5)}_{\Phi_1\Phi_2\ldots\Phi_k} \\ &\times \int_0^{\pi R} \left[1 + r\{\delta(y) + \delta(y-\pi R)\}\right] \phi_1\phi_2\ldots\phi_k dy \end{aligned}$$

Boltzmann equation and relic density

- The relic abundance of a particle species χ which was in thermal equilibrium in the early universe and decoupled when it became non-relativistic, is obtained by solving the Boltzmann equation for the evolution of the χ number density n,

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2)$$

- At high temperature ($T \gg m$), $n_{eq} \sim T^3$ and
  at low temperature ($T \ll m$), $n_{eq} = g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$.

Co-annihilation

- If the relic particle χ_1 is nearly degenerate with other particles $(\chi_2, \chi_3, \ldots, \chi_N)$ in the spectrum, then its relic abundance gets reasonable contributions from the annihilations of nearly degenerate particles. [Griest and Seckel, PRD **43**, 3191, '91]
- In this case, Boltzmann equation will be,

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

where,

$$\begin{aligned}
\sigma_{eff}(x) &= \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{eff}^2} (1+\Delta_i)^{3/2} (1+\Delta_j)^{3/2} \exp\left(-x(\Delta_i + \Delta_j)\right), \\
g_{eff}(x) &= \sum_{i=1}^{N} g_i (1+\Delta_i)^{3/2} \exp\left(-x\Delta_i\right), \\
\Delta_i &= \frac{m_i - m_1}{m_1}
\end{aligned}$$

Co-annihilation

where $x = \frac{m}{T}$, $\sigma_{ij} \equiv \sigma(\chi_i \chi_j \to SM, SM)$ and $n = \sum_{i=1}^{N} n_i$, and g_i is the internal degrees of freedom (DoF) of the i-th particle.

- From this consideration,

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

where,

$$\begin{aligned} I_a &= x_F \int_{x_F}^{\infty} a_{eff}(x) x^{-2} dx, \\ I_b &= 2x_F^2 \int_{x_F}^{\infty} b_{eff}(x) x^{-3} dx, \end{aligned}$$

and $g_*(x_F)$ is the total number of effectively massless DoF.

Co-annihilation

- The freeze-out temperature x_F can be approximated as,

$$x_F = \ln\left(\frac{5}{4}\sqrt{\frac{45}{8}}\frac{g_{eff}(x_F)}{2\pi^3}\frac{mM_{Pl}\left[a_{eff}(x_F) + 6b_{eff}(x_F)/x_F\right]}{\sqrt{g_*(x_F)x_F}}\right).$$

- a_{eff} and b_{eff} are given by,

$$\begin{aligned} a_{eff}(x) &= \sum_{ij}^{N} a_{ij}\frac{g_i g_j}{g_{eff}^2}(1+\Delta_i)^{3/2}(1+\Delta_j)^{3/2}\exp\left(-x(\Delta_i+\Delta_j)\right), \\ b_{eff}(x) &= \sum_{ij}^{N} b_{ij}\frac{g_i g_j}{g_{eff}^2}(1+\Delta_i)^{3/2}(1+\Delta_j)^{3/2}\exp\left(-x(\Delta_i+\Delta_j)\right), \end{aligned}$$

and a_{ij}, b_{ij} are obtained from $\sigma_{ij}v = a_{ij} + b_{ij}v^2 + \mathcal{O}(v^4)$.

Results for $B^{(1)}$ LKP

- In nmUED the masses as well as the couplings of the KK-excitations strongly depends on BLKT parameters.
- These parameters consequently determines the mass spectrum, i.e., the identity of LKP or which particles will contribute in co-annihilation.
- This flexibility in nmUED can make any of $\nu^{(1)}$, $H^{(1)}$, $W_3^{(1)}$ or $B^{(1)}$ an LKP. We'll consider the $B^{(1)}$ and $W_3^{(1)}$ LKP case.

Results for $B^{(1)}$ LKP

- The masses of the $n = 1$ KK-states are determined by their respective BLKT parameters r_i or equivalently, $R_i = \frac{r_i}{R}$.
- Consider $B^{(1)}$ to be the LKP. For simplicity assume only leptons are next heavier in mass. So their co-annihilation is to be taken into account.
- Similar exercise in mUED, with $B^{(1)}$ LKP allows the compactification scale R^{-1} to be within the range 500-600 GeV. [Kong and Matchev, JHEP **0601** 038 '06]
- From recent Planck data the relic abundance, $\Omega h^2 = 0.1198 \pm 0.0026$.

  [P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1303.5076[astro-ph.CO]]

Results for $B^{(1)}$ LKP

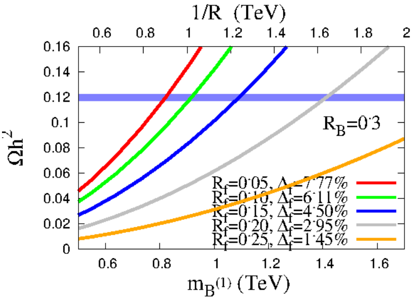

Figure: Variation of Ωh^2 with relic $B^{(1)}$ mass.

Result for $W_3^{(1)}$ LKP

- To avoid fermion LKP we always choose R_B, $R_W > R_f$.
- The choice of BLKTs, $R_W > R_B$ makes $W_3^{(1)}$ LKP.

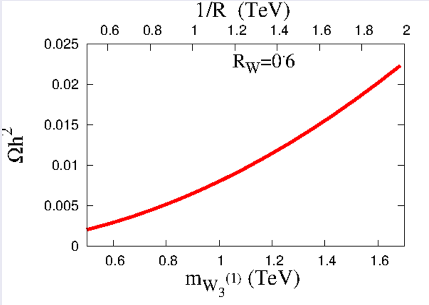

Figure: Variation of Ωh^2 with $W_3^{(1)}$ mass

Direct detection prospects of $B^{(1)}$

- The spin dependent and spin independent or scalar cross sections of $B^{(1)}$ scattering off Xenon ($Z = 54$, $A = 131$) nuclei are estimated.
- DM-nucleon cross sections are given by,

$$\sigma_{p,n}^{\text{scalar}} = \frac{m_N^2 m_{p,n}^2}{4\pi\mu^2 A^2 (m_{B^{(1)}} + m_N)^2} \left(Z f_p^{B^{(1)}} + (A - Z) f_n^{B^{(1)}} \right)^2 ,$$

$$\sigma_{p,n}^{\text{spin}} = \frac{\tilde{g}_1^4}{2\pi} \frac{\mu_{p,n} a_{p,n}^2}{\left(m_{B^{(1)}}^2 - m_{f^{(1)}}^2 \right)^2} ,$$

where $\mu_{p,n}(\mu)$ is the reduced mass of the DM-nucleon(-nucleus) system, $a_{p,n}$ are nuclear parameters, m_N is the nuclear mass, $f_p^{B^{(1)}}$ and $f_n^{B^{(1)}}$ are some kinematic factors which also contains various nuclear parameters.

Spin independent cross sections

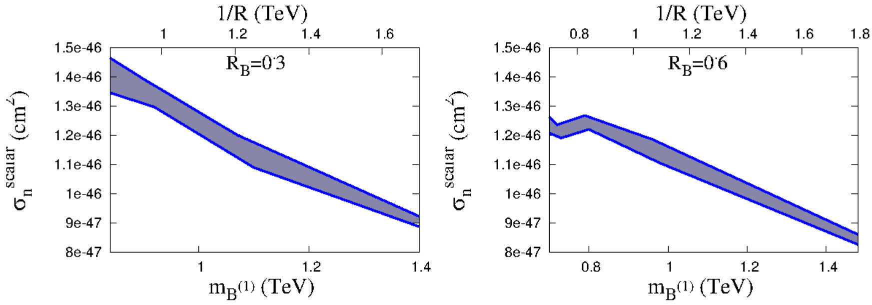

Figure: Variation of spin independent DM-nucleon cross section with the relic particle mass for Xenon.

Spin dependent cross sections

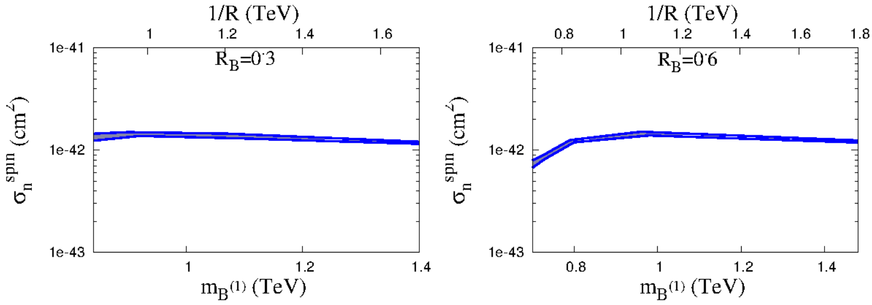

Figure: Variation of spin dependent DM-nucleon cross section with the relic particle mass for Xenon.

Summary

- In nmUED, BLKTs with same strength at both the boundaries can preserve KK-parity assuring the possibility of stable LKP.
- The choice of parameters determine the identity of the LKP.
- We consider the possibility of $B^{(1)}$ and $W_3^{(1)}$ LKP.
- Recent observational data on DM from Planck constrains the nmUED parameter space. Allowed range of R^{-1} can be relaxed from its mUED prediction of $0.5 - 0.6$ TeV.