Phenomenology of Non-minimal universal extra dimensions

Tom Flacke

University of Michigan

based on: TF, A. MENON and D. PHALEN [PRD 79, 056009 (2009)]

and work in progress with K. FREESE, D. HOOPER, and A. MENON

Outline

- Review on Universal Extra Dimensions (UED)
- UED and boundary localized terms (BLTs)
  - Toy model: a massive 5D scalar field with BLTs
  - The electroweak sector of UED with BLTs
  - UED with $W^{3(1)}$ dark matter
  - Some results from UED with BLTs
- $W^{3(1)}$ dark matter phenomenology
  - Overview
  - $W^{3(1)}$ dark matter and neutrinos from the sun
- Conclusions and Outlook

Outline

- Review on Universal Extra Dimensions (UED)
- UED and boundary localized terms (BLTs)
  - Toy model: a massive 5D scalar field with BLTs
  - The electroweak sector of UED with BLTs
  - UED with $W^{3(1)}$ dark matter
  - Some results from UED with BLTs
- $W^{3(1)}$ dark matter phenomenology
  - Overview
  - $W^{3(1)}$ dark matter and neutrinos from the sun
- Conclusions and Outlook

Outline

- Review on Universal Extra Dimensions (UED)
- UED and boundary localized terms (BLTs)
  - Toy model: a massive 5D scalar field with BLTs
  - The electroweak sector of UED with BLTs
  - UED with $W^{3(1)}$ dark matter
  - Some results from UED with BLTs
- $W^{3(1)}$ dark matter phenomenology
  - Overview
  - $W^{3(1)}$ dark matter and neutrinos from the sun
- Conclusions and Outlook

Outline

- Review on Universal Extra Dimensions (UED)
- UED and boundary localized terms (BLTs)
  - Toy model: a massive 5D scalar field with BLTs
  - The electroweak sector of UED with BLTs
  - UED with $W^{3(1)}$ dark matter
  - Some results from UED with BLTs
- $W^{3(1)}$ dark matter phenomenology
  - Overview
  - $W^{3(1)}$ dark matter and neutrinos from the sun
- Conclusions and Outlook

UED review

- UED models are models with flat, compact extra dimensions in which *all* fields propagate. [Appelquist, Cheng, Dobrescu,(2001)]
- The Standard Model (SM) particles are identified with the lowest-lying modes of the respective Kaluza-Klein (KK) towers.
- In order to obtain chiral fermions in the KK-decomposition, the extradimension is compactified on an orbifold (for 5D UED $\rightarrow S^1/Z^2$).
- The underlying 5D parameters are fixed by matching the zero mode couplings and masses to the SM values.

Main UED features (at tree-level):

- Every Standard Model field is accompanied by an infinite tower of partner-fields - its KK-excitations.
- The masses of the KK-excitations of any field A are $m_A^{2(n)} = (n/R)^2 + m_A^{2(0)}$.
- The 5D couplings are related to the SM couplings by $\hat{g}_i^2 = g_i^2 \pi R$, $\hat{\lambda} = \lambda \pi R$, and $\hat{\mu} = \mu$.
- 5D momentum conservation implies conservation of KK-number in interactions.
- In particular, this implies that the lightest KK particle (LKP) is stable $\rightarrow$ a dark matter candidate.

UED as an effective field theory

- UED is a five dimensional model
  $\rightarrow$ non-renormalizable.
- It should be considered as an effective field theory
  with a cutoff Λ.
- Naive dimensional analysis (NDA) result: $\Lambda \sim 50/R$.
  This cutoff is low!
- Bounds from unitarity imply $\Lambda \sim \mathcal{O}(10)$ [Chivukula, Dicus, He (2001)]
- *Without knowledge of the underlying theory*
  all operators allowed by all symmetries should be considered.

This in particular includes operators which are localized on the orbifold fixed points but otherwise respect all SM symmetries.

- These operators break 5D translation invariance which however is broken anyway when compactifying on S^1/Z_2.
- The Z_2 symmetry dictates that the operators are included symmetrically on both branes.
- KK-number is broken in the presence of such operators, but the Z_2 symmetry guarantees that KK-parity is still conserved $\rightarrow$ the LKP remains stable.
- Example

$$S_{tot} \supset \int d^5x \frac{r_W}{4\hat{g}_2^2} W_{\mu\nu} W^{\mu\nu} \left(\delta(y) + \delta(y - \pi R)\right)$$

Naive dimensional analysis implies: $r_W/R \sim 6\pi/(\Lambda R)$.

- An analogous BLT exists for *every* term in the UED bulk action.

$$S_{UED,bulk} = S_g + S_H + S_f$$

with

$$\begin{aligned}
S_g &= \int d^5x \left\{ -\frac{1}{4\hat{g}_3^2} G^A_{MN} G^{AMN} - \frac{1}{4\hat{g}_2^2} W^I_{MN} W^{IMN} - \frac{1}{4\hat{g}_Y^2} B_{MN} B^{MN} \right\} \\
S_H &= \int d^5x \left\{ (D_M H)^\dagger (D^M H) + \hat{\mu}^2 H^\dagger H - \hat{\lambda} (H^\dagger H)^2 \right\} \\
S_f &= \int d^5x \left\{ i\overline{\psi}\gamma^M D_M \psi + \left(\hat{\lambda}_E \overline{L} E H + \hat{\lambda}_U \overline{Q} U \tilde{H} + \hat{\lambda}_D \overline{Q} D H + \text{h.c.} \right) \right\}
\end{aligned}$$

Toy model: a massive 5D scalar field with BLTs

[generalization of Dvali *et al.* (2001); Carena, Tait and Wagner (2002)]

$$S_{bulk} = \int d^5x \frac{1}{2}\partial^M\Phi\partial_M\Phi - \frac{\hat{m}^2}{2}\Phi^2$$

$$S_{bd} = \int d^4x \left(\frac{r_\Phi}{2}\partial^\mu\Phi\partial_\mu\Phi - \frac{m_b^2}{2}\Phi^2\right)|_{y=0,\pi R}$$

Resulting EOMs and boundary conditions are

$$0 = (\Box - \partial_5^2 + \hat{m}^2)\Phi$$

$$0 = [-\partial_5 + (r_\Phi\Box + m_b^2)]\Phi|_{y=0}$$

$$0 = [\partial_5 + (r_\Phi\Box + m_b^2)]\Phi|_{y=\pi R}$$

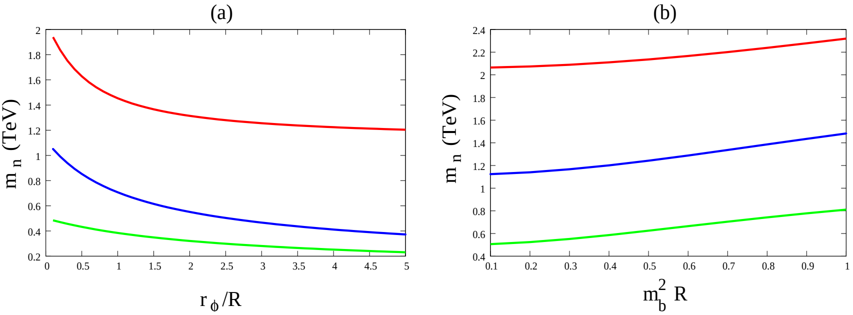
- Decomposing $\Phi(x,y) = \sum_n \phi^{(n)}(x) f_n(y)$

  yields the determining equation for the KK masses:

$$\frac{(r_\Phi m_\alpha^2 - m_b^2)}{M_\alpha} = \begin{cases} \tanh(\frac{M_\alpha \pi R}{2}) & \text{even} \\ \coth(\frac{M_\alpha \pi R}{2}) & \text{odd} \end{cases}$$

$$\frac{(r_\Phi m_n^2 - m_b^2)}{M_n} = \begin{cases} -\tan(\frac{M_n \pi R}{2}) & \text{even} \\ \cot(\frac{M_n \pi R}{2}) & \text{odd} \end{cases}$$

where $M_\alpha = \sqrt{\hat{m}^2 - m_\alpha^2}$ & $M_n = \sqrt{m_n^2 - \hat{m}^2}$



(a) change of the KK spectrum for varying r_Φ with $R^{-1} = 1\,\text{TeV}$, $m = .5\,\text{TeV}$, $m_b = 0$

(b) change of the KK spectrum for varying m_b with $R^{-1} = 1\,\text{TeV}$, $m = .5\,\text{TeV}$, $r_\Phi = 0$

Qualitative features for UED with BLTs:

- The KK-masses are modified (lowered by kinetic and raised by mass boundary terms).
- The 4D to 5D coupling relations are modified.
- The KK-mode couplings are *not* equal to the zero mode couplings.
- 5D momentum conservation is broken by the Z_2 which implies KK-number violation, *but* a KK-parity is still conserved.
- This implies that the LKP is stable.

BLTs in the eletroweak sector

- On top of the UED bulk action we allow for boundary terms

$$
\begin{aligned}
S_{BLT} &= \int d^5x\,[\delta(y)+\delta(y-\pi R)]\times \\
&\Big(-\frac{r_B}{4}B_{\mu\nu}B^{\mu\nu}-\frac{r_W}{4}W^a_{\mu\nu}W^{a\mu\nu} \\
&+r_H(D^\mu H)^\dagger D_\mu H+\mu_b H^\dagger H-\lambda_b(H^\dagger H)^2\Big)\,,
\end{aligned}
$$

  where for simplicity, we assume $v_b \equiv \sqrt{\mu_b^2/\lambda_b} = \sqrt{\hat{\mu}^2/\hat{\lambda}} \equiv \hat{v}$.

- Gauge fixing the action with an $R\xi$-type gauge, the EOM and boundary conditions for the gauge and Higgs fields are found. (see [TF, Menon, Phalen [PRD 79, 056009], Appendix B] for details)

Result:

$$\frac{(r_\Phi m_\alpha^2 - m_b^2)}{M_\alpha} = \begin{cases} \tanh(\frac{M_\alpha \pi R}{2}) & \text{even} \\ \coth(\frac{M_\alpha \pi R}{2}) & \text{odd} \end{cases}$$

$$\frac{(r_\Phi m_n^2 - m_b^2)}{M_n} = \begin{cases} -\tan(\frac{M_n \pi R}{2}) & \text{even} \\ \cot(\frac{M_n \pi R}{2}) & \text{odd}, \end{cases}$$

where $M_\alpha = \sqrt{m^2 - m_\alpha^2}$, $M_n = \sqrt{m_n^2 - m^2}$ and the bulk mass, brane mass and brane kinetic parameter for each particle is

	m	m_b	r_Φ
W	$\hat{g}_2^2 \hat{v}^2/4$	$r_H \hat{g}_2^2 \hat{v}^2/4$	r_W
Z	$(\hat{g}_2^2 + \hat{g}_Y^2)\hat{v}^2/4$	$r_H(\hat{g}_2^2 + \hat{g}_Y^2)\hat{v}^2/4$	r_W (if $r_B = r_W$)
γ	0	0	r_W (if $r_B = r_W$)
h	$\hat{\mu}$	μ_b	r_H
$a_\pm$	$\hat{g}_2^2 \hat{v}^2/4$	$r_H \hat{g}_2^2 \hat{v}^2/4$	r_H
a_0	$(\hat{g}_2^2 + \hat{g}_Y^2)\hat{v}^2/4$	$r_H(\hat{g}_2^2 + \hat{g}_Y^2)\hat{v}^2/4$	r_H

With the wave functions determined, we can calculate:

- The zero mode spectrum in terms of the 5D parameters

  $\rightarrow$ determines the 4D to 5D parameters identification.

- The modified KK mode spectrum

  $\rightarrow$ the LKP is not necessarily the $B^{(1)}$.

- The modified KK mode couplings

  $\rightarrow$ overlap integrals of the KK wave functions.

The programme to match non-minimal UED to the SM:

- Set the parameters $R, r_H, r_B, r_W, (\mu_b, \lambda_b)$.
- Determine the underlying parameters $\hat{g}_2, \hat{g}_Y, \hat{v}, (\hat{\mu})$
  from the measured SM parameters $\alpha, G_f, m_W, m_Z, (m_h)$.
- This matching over-constrains $\hat{g}_2, \hat{g}_Y, \hat{v}, (\hat{\mu})$
  $\rightarrow$ one obtains a bound on $R, r_H, r_B, r_W, (\mu_b, \lambda_b)$.
- If the parameter point $R, r_H, r_B, r_W, (\mu_b, \lambda_b)$ is allowed,
  determine the masses of the first KK modes to identify the LKP.

KK $W^{3(1)}$ dark matter

As one example, we choose $r_H = r_B = 0, r_W \neq 0$

- The first KK mode masses of $W^{\pm}$ and W^3 are reduced while all other modes remain at R^{-1}.

  $\rightarrow$ A candidate model for $W^{3(1)}$ dark matter.

What happens qualitatively?

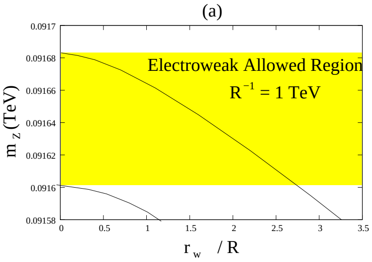
The neutral gauge boson mass matrix at the first KK level is

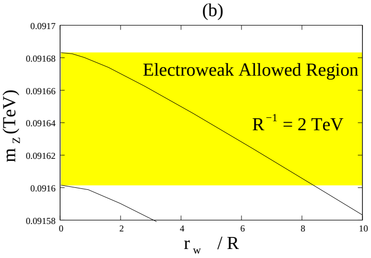
$$M^2_{B^{(1)},W^{3(1)}} = \begin{pmatrix} m^2_{B^{(1)}} & \mathcal{M}^2_{1,1} \\ \mathcal{M}^2_{1,1} & m^2_{W^{3(1)}} \end{pmatrix},$$

where $\mathcal{M}^2_{1,1}$ is determined by an overlap integral.

- The LKP is (approx.) the lighter eigenstate of this matrix.
- If $m^2_{W^{3(1)}} < m^2_{B^{(1)}}$, the LKP is mostly $W^{3(1)}$.

Quantitative results: Bounds from matching to the SM.

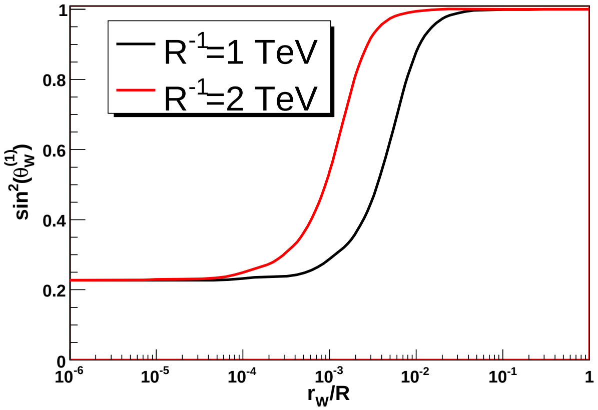




Variation of m_Z^{nUED} for different values of r_W with $R^{-1} = 1\,\text{TeV}$ and $R^{-1} = 2\,\text{TeV}$ in the $r_W \neq 0 = r_B = r_H$ scenario.

- The yellow band corresponds to the 2σ allowed tree-level value of m_Z^{tree}.
- The region within the black lines is the 2σ predicted tree-level value of m_Z^{nUED}.

Results for dark matter:



Modification of the Weinberg angle of the first KK mode as at $R^{(-1)} = 1\,\mathrm{TeV}$ (black) and $R^{(-1)} = 2\,\mathrm{TeV}$ (red).

We studied the $W^{3(1)}$, and several other sample scenarios.

Some results:

- For $O(1)$ BLKTs in the electroweak sector, the first KK mode masses for EW gauge bosons and KK fermions can be split substantially (we found factors of up to 5).
- A scalar Higgs LKP $h^{(1)}$ can be achieved, but requires $\mathcal{O}(1)$ BLKTs and is highly constrained for low R^{-1}.
- A $W^{3(1)}$-like LKP is easily achieved, with values of $(r_W - r_B) > \mathcal{O}(10^{-2})$.
- A pseudo-scalar Higgs LKP ($a^{0(1)}$) cannot be achieved with the BLTs we considered.

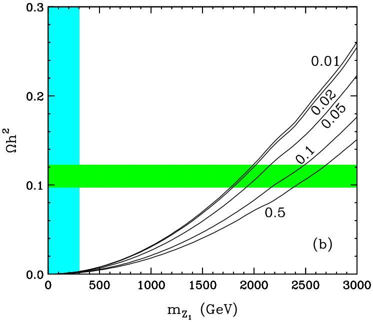
An Application: $W^{3(1)}$ dark matter and neutrinos from the sun

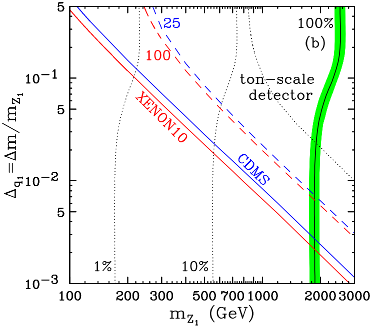
We showed that boundary kinetic terms modify the KK spectrum and can thereby change the LKP.

WIMPs at the first KK level of UED:

- $U(1)_Y$ gauge boson $B^{(1)}$ $\rightarrow$ the "standard" UED DM candidate,
- neutral SU(2) gauge boson $W^{3(1)}$,
- scalar Higgs KK partner $h^{(1)}$ $\rightarrow$ is strongly constrained by SM matching,
- pseudoscalar Higgs KK partner $a^{0(1)}$ $\rightarrow$ no explicit models known,
- KK neutrino $\nu^{(1)}$ $\rightarrow$ is experimentally disfavored [Servant, Tait (2002)]

Only existing study of $W^{3(1)}$ dark matter: [Arrenberg, Baudis, Kong, Matchev, Yoo (2008)]





- Left: Thermal relic density of the $W^{3(1)}$ as a function of $m_{W^{3(1)}}$ for several values of $\Delta q \equiv (m_{q^{(1)}} - m_{W^{3(1)}})/m_{W^{3(1)}}$.
- Right: constraints on $m_{W^{3(1)}}$ and Δq from direct detection.

Indirect DM detection from neutrinos via DM annihilation in the sun.

(in collaboration with K. Freese, D. Hooper, and A. Menon).

The basic idea:

- Dark matter is captured by the sun via scattering with the sun's nuclei.
- It accumulates and eventually annihilates.

  For $W^{(1)}$ we are in steady state

  $\rightarrow$ the annihilation rate is given by the capture rate.
- Amongst the direct or indirect annihilation products are neutrinos which are radiated out of the sun and lead to an excess of the sun's neutrino flux which can be detected by SuperK or ICECUBE.

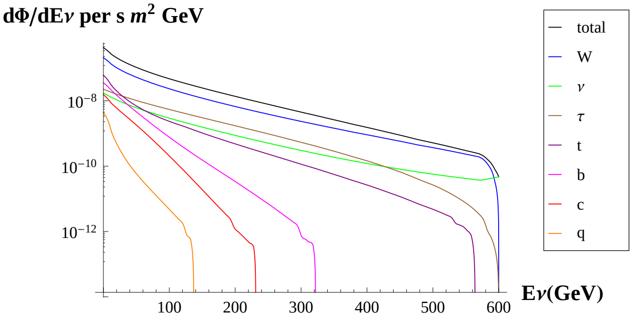
- Lets look at the annihilation first:

  The main annihilation channel is $W^{3(1)}W^{3(1)} \to W^+W^-$ via T-channel exchange of a charged KK W, while annihilations to fermions are subdominant

$$
\begin{aligned}
< \sigma v >_{W^{3(1)}W^{3(1)} \to W^+W^-} &= \frac{g_2^4}{m^2_{W^{3(1)}}} \frac{19}{72\pi} + \mathcal{O}(\beta) \\
< \sigma v >_{W^{3(1)}W^{3(1)} \to f\bar{f}} &= \frac{g_2^4}{m^2_{W^{3(1)}}} \frac{3N_c}{256\pi} + \mathcal{O}(\beta).
\end{aligned}
$$

Results for neutrinos from DM annihilations in the sun. (PRELIMINARY)

Applying neutrino propagation results of [Cirelli *et al.*, (2005)]



- Contributions to $\frac{d\Phi}{dE_\nu}(E_\nu)$ at earth (for $m_{W^{3(1)}} = 600\,\mathrm{GeV}$, $r_q = 0.14$).

- The capture rate is determined by $W^{3(1)}$ scattering off nuclei via T-channel exchange of a KK quark with a cross section

$$\sigma_{H,SD,W} = \frac{g_2^4 m_N}{128 m_{W^{3(1)}}^4 r^2} (\Delta_u^p + \Delta_d^p + \Delta_s^p)^2,$$

where

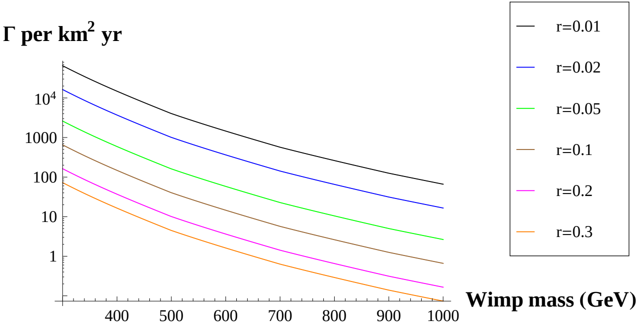
$$r \equiv \frac{m_{q_L^{(1)}} - m_{W^{3(1)}}}{m_{W^{3(1)}}}.$$

and

$$\Delta_u^p = 0.78 \pm 0.02 \, \Delta_d^p = -0.48 \pm 0.02 \, \Delta_d^p = -0.15 \pm 0.07.$$

Following the standard procedure [Jungman *et al.*, 1996], we calculate the rate per unit detector area for neutrino-induced throughgoing-muon events Γ_{detect}.

Results (PRELIMINARY; only including the light elements in the sun)



Conclusions

- UED models are effective field theories with a low cutoff.
- The full UED parameter space includes boundary localized operators.
- Phenomenological studies so far focussed on a small subspace $\longrightarrow$
  - old UED bounds can be affected,
  - the new parameters ought to be constrained by existing data,
  - large potential for novel signatures at colliders and for dark matter.
- We provided a “toolbox”

  to study the electroweak sector of non-minimal UED at tree-level.
- Application: the $W^{3(1)}$ represents a dark matter candidate from UED.
- We presented first (preliminary) results on indirect $W^{3(1)}$ dark matter detection via neutrinos.

Outlook

Theory questions:

- Implications of fermion BLKTs?
- One-loop corrections to non-minimal UED? generalization of [Cheng,Matchev,Schmaltz]
- How do BLKTs arise from an underlying theory?

Phenomenology of UED with $W^{3,(1)}$ dark matter:

- Changes of UED collider constraints
  - Bounds from non-detection of KK-modes? eg. a la [Rizzo; Macesanu *et al.*]
  - Modification of bounds from EWPT ?eg. a la [Appelquist, Yee]
  - Modifications of other collider bounds? see UED review of [Hooper, Profumo]
  - Novel signatures?
- Changes to DM bounds:
  - Indirect detection: $\overline{p}$, e^+, γ, synchrotron radiation, ...? [Bergstrom *et al.*; Brinkmann; ...]
  - Comparison to Wino DM? [Kane *et al.*]