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
- NUED sample scenarios
  - “split" UED
  - a Higgs LKP from UED (?)
  - a $W^{(3)}$ LKP from UED (!)
- $W^{3(1)}$ dark matter phenomenology
  - Overview
  - $W^{3(1)}$ dark matter and neutrinos from the sun
- Conclusions and Outlook

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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.

Disclaimer

Here, I will focus on the *simplest* UED model.

- One flat extra dimension only $\rightarrow S^1/Z_2$.

  (For work in 6D, see Dobrescu *et al.*. (2004 ff); Chris Jackson's talk)
- Only Standard Model fields and their KK modes.
- No background fields.

  (For fermion bulk masses via a background field see Jing Shu's talk)

UED "common knowledge"

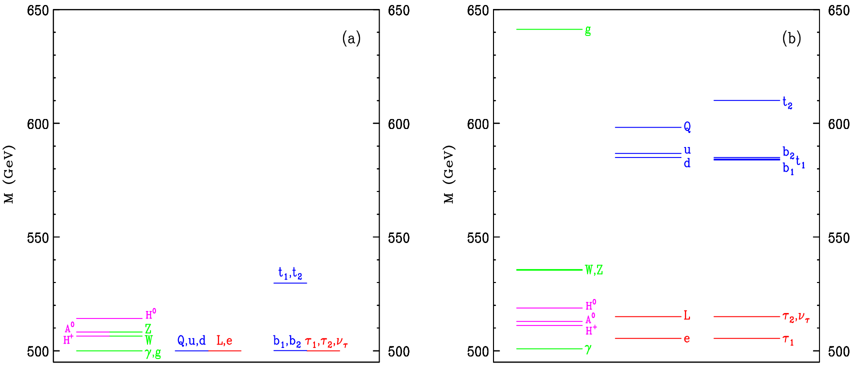
Main UED features:

- 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 $\hat{\mu} = \mu$.*
- The couplings at zero mode and higher KK mode level are the same.*
- 5D momentum conservation $\rightarrow$ conserved KK-number in interactions.*
- In particular, this implies that the lightest KK particle (LKP) is stable $\rightarrow$ a dark matter candidate.

* not exact, but corrections are considered to be small (loop suppressed)

Tree level and one-loop corrected MUED spectrum:

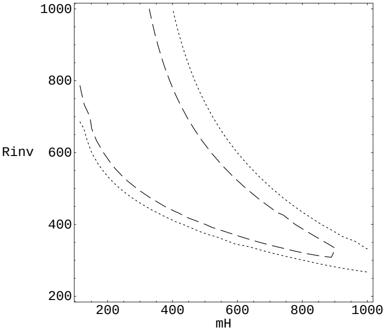
[Cheng, Matchev, Schmaltz, PRD **66** (2002) 036005, hep-ph/0204342]



Mini 5D (M)UED pheno review

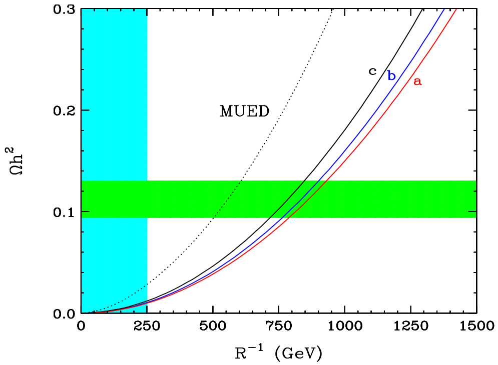
- Phenomenological constraints on R^{-1}
  - lower bound $\Rightarrow$ $R^{-1} \gtrsim 300\,\mathrm{GeV}$
    - no detection of KK-modes [Appelquist *et al.* (2001); Rizzo (2001); Macesanu *et al.* (2002)]
    - FCNCs [Buras, Weiler *et al.* (2003)]
    - EWPT [Appelquist, Yee (2002)]
  - upper bound: preventing over closure of the Universe by $B^{(1)}$ dark matter
    $\Rightarrow$ $R^{-1} \lesssim 1.5\mathrm{TeV}$ [Servant, Tait (2002); Matchev, Kong (2005); Burnell, Kribs (2005)]
- Distinguishing UED and SUSY at LHC
  [Datta, Kong, Matchev (2005); Smillie, Webber (2005); Kane *et al.* (2005, 2008); Csaki *et al.* (2007)]; see also talk by Zhenyu Han
- For a review see [Hooper,Profumo (2007)]

Electroweak precision tests:



95% (dashed line) and 99% (dotted line) confidence limit exclusion zones for the UED model as a function of Higgs mass in the range 115 GeV to 1 TeV,
and mass $M_1 = 1/R$ of the lightest KK excitation in the range 200 GeV to 1 TeV

[Kong, Matchev, JHEP **0601** (2006) 038, hep-ph/0509119]



Relic density of the LKP as a function of R^{-1} in the Minimal UED model.

- Red line is the result from considering $\gamma_1 \gamma_1$ annihilation only.
- Dotted line is the result from the full calculation in MUED.
- Green horizontal band denotes the preferred WMAP region $0.094 < \Omega_{CDM} h^2 < 0.129$.
- Cyan vertical band delineates values of R^{-1} disfavored by precision data.

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

$$S_g = \int d^5x \left\{ -\frac{1}{4\hat{g}_3^2} G^A_{MN} G^{AMN} - \frac{1}{4\hat{g}_2^2} W^I_{MN} W^{IMN} - \frac{1}{4\hat{g}_Y^2} B_{MN} B^{MN} \right\}$$

$$S_H = \int d^5x \left\{ (D_M H)^\dagger (D^M H) + \hat{\mu}^2 H^\dagger H - \hat{\lambda}(H^\dagger H)^2 \right\}$$

$$S_f = \int d^5x \left\{ i\overline{\psi}\gamma^M D_M \psi + \left(\hat{\lambda}_E \overline{L} E H + \hat{\lambda}_U \overline{Q} U \tilde{H} + \hat{\lambda}_D \overline{Q} D H + \text{h.c.} \right) \right\}$$

Toy model: a massive 5D scalar field with BLTs

[generalization of Dvali *et al.* (2001); Carena, Tait and Wagner (2002); Santiago *et al.*(2003ff)]

$$\begin{aligned} S_{bulk} &= \int d^5x \frac{1}{2}\partial^M\Phi\partial_M\Phi - \frac{\hat{m}^2}{2}\Phi^2 \\ S_{bd} &= \int d^4x \left(\frac{r_\Phi}{2}\partial^\mu\Phi\partial_\mu\Phi - \frac{m_b^2}{2}\Phi^2\right)|_{y=0,\pi R} \end{aligned}$$

Resulting EOMs and boundary conditions are

$$\begin{aligned} 0 &= (\Box - \partial_5^2 + \hat{m}^2)\Phi \\ 0 &= [-\partial_5 + (r_\Phi\Box + m_b^2)]\Phi|_{y=0} \\ 0 &= [\partial_5 + (r_\Phi\Box + m_b^2)]\Phi|_{y=\pi R} \end{aligned}$$

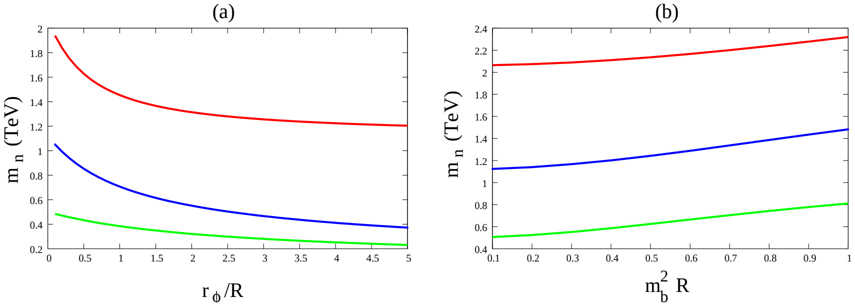
- Decomposing $\Phi(x,y) = \sum_n \phi^{(n)}(x) f_n(y)$

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

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

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

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.

NUED sample scenarios

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.

In detail, we match in the following way:

- We calculate G_f and m_W which are determined from the *charged* sector.
- We then use (G_f, m_W) to determine $(\hat{g}_2, \hat{v})$.
- We calculate α to fix $\hat{g}_Y$.
- Thereby m_Z is determined,

  which we compare to the tree-level SM value defined by

$$m_Z^{tree}(m_W, G_f, \alpha) \equiv \lim_{R, r_W, \ldots \to 0} m_Z^{nUED}(R, r_W, ..., m_W, G_f, \alpha)$$

Scenario I: Split UED

We choose a uniform boundary kinetic term $r_{EW} \equiv r_H = r_B = r_W \neq 0$.

- Main modification in the KK mass spectrum:

  The electroweak partner KK masses are reduced wrt. to the fermionic KK partners ("split UED").

- The LKP wave function is modified.

  $\Rightarrow$ the couplings of the LKP are modified.

- Matching relations:

$$m_W^{\pm(0)} = m_W$$

$$G_f = \frac{\hat{g}_2^2}{4\sqrt{2}\pi R}\sum_{n=0}^{\infty}\frac{b_{2n}}{m^2_{W(2n)}}$$

  - where

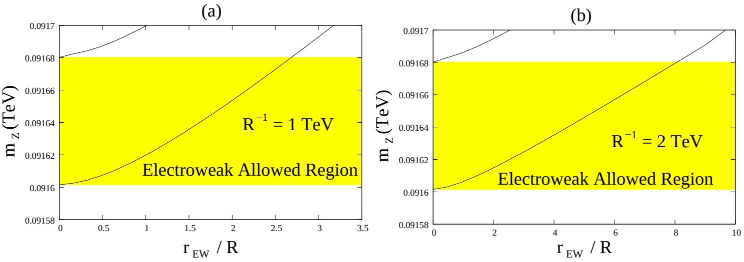
$$b_0 = \frac{1}{1+\frac{2r_{EW}}{\pi R}}$$

$$b_{2n} = \left(\frac{8\sin^2\frac{M^W_{2n}\pi R}{2}}{\left(1+\frac{\sin M^W_{2n}\pi R}{M^W_{2n}\pi R}+\frac{4r_{EW}}{\pi R}\cos^2\frac{M^W_{2n}\pi R}{2}\right)\left(M^W_{2n}\pi R\right)^2}\right)$$

- and

$$\alpha_{em} = \frac{1}{4\pi(\pi R+2r_{EW})}\frac{\hat{g}_Y^2\hat{g}_2^2}{\hat{g}_Y^2+\hat{g}_2^2}$$

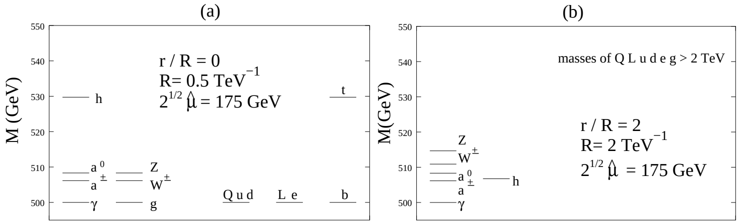
As constraints from the tree-level m_Z mass we find



Variation of m_Z^{nUED} for different values of r_{EW} with $R^{-1} = 1$ TeV and $R^{-1} = 2$TeV.

- 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}.

A sample mass spectrum:



Sample spectra for UED.

(a) The tree level UED spectrum without BLTs (first KK level) for $R^{-1} = 500\text{GeV}$.

(b) The tree level UED spectrum with $r_B = r_W = r_H = 2R$, $\mu_b = 0$, $R^{-1} = 2\text{TeV}$ and $m_h = 115\text{GeV}$.

- Parameters are chosen such that the LKP mass of both models coincide.

Scenario II: KK Higgs dark matter

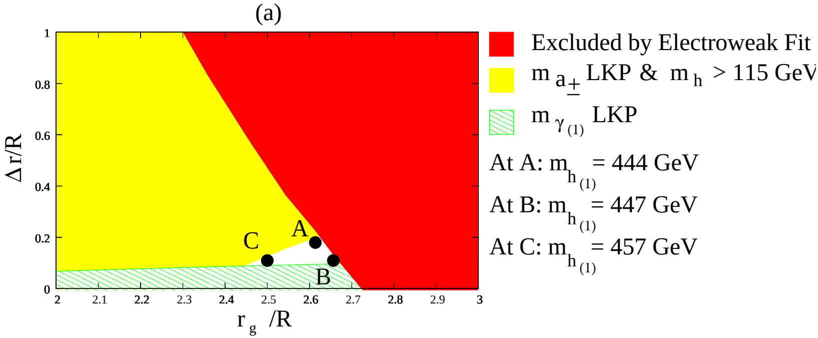
We now choose $r_g \equiv r_W = r_B < r_H$.

- Here, the Higgs KK masses are more strongly reduced than the gauge KK masses.
  $\Rightarrow$ A candidate model for $h^{(1)}$ or $a^{0(1)}$ LKP.
- From the EOM and the boundary conditions it follows that

$$\begin{aligned} m_{Z^{(1)}} &\geq m_{a^{0(1)}} > m_{a^{\pm(1)}} \\ m_{Z^{(1)}} &> m_{W^{\pm(1)}} \geq m_{a^{\pm(1)}} \\ m_{W^{\pm(1)}} &> m_{\gamma^{(1)}} \end{aligned}$$

- The LKP in this scenario is $\gamma^{(1)}$,$a^{\pm(1)}$, or $h^{(1)}$.

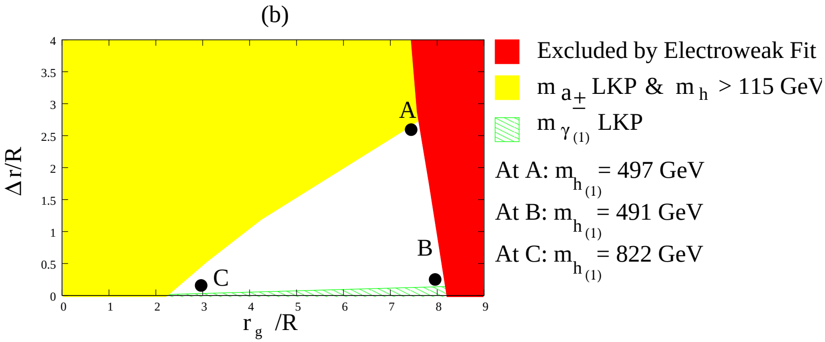
Results for dark matter candidates: $R^{-1} = 1$ TeV



LKP phase space in the $r_g \equiv r_B = r_W \neq r_H$ scenario for $R^{-1} = 1$ TeV.

- The Higgs brane mass parameter has been set to $\mu_b = 0$ and the zero mode Higgs mass has been set to 115 GeV.
- In the white region the LKP is the KK Higgs.

Results for dark matter candidates: $R^{-1} = 2\,\mathrm{TeV}$



LKP phase space in the $r_g \equiv r_B = r_W \neq r_H$ scenario.

- The Higgs brane mass parameter has been set to $\mu_b = 0$ and the zero mode Higgs mass has been set to $115\,\mathrm{GeV}$.
- In the white region the LKP is the KK Higgs.

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

As a third 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?

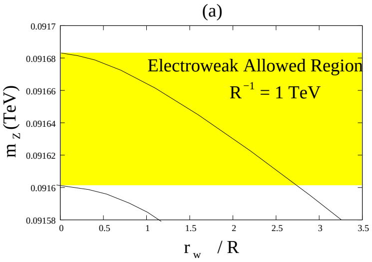
The neutral gauge boson mass matrix at the first KK level is

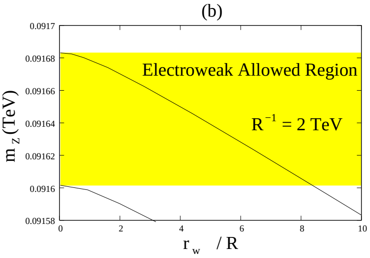
$$M^2_{B^{(1)},W^{3(1)}} = \begin{pmatrix} m^2_{B^{(1)}} & \mathcal{M}^2_{1,1} \\ \mathcal{M}^2_{1,1} & m^2_{W^{3(1)}} \end{pmatrix},$$

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.

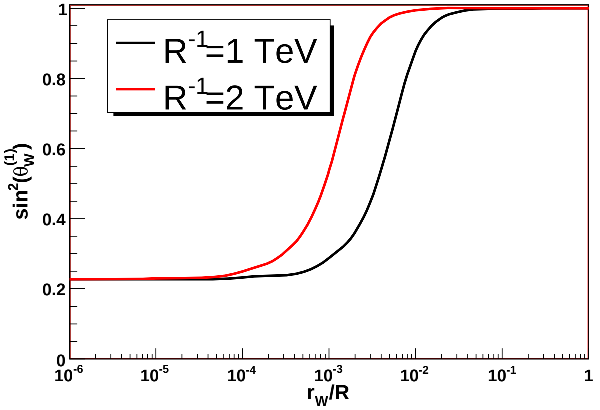




Variation of m_Z^{nUED} for different values of r_W with $R^{-1} = 1\,\mathrm{TeV}$ and $R^{-1} = 2\,\mathrm{TeV}$ in the $r_W \neq 0 = r_B = r_H$ scenario.

- 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).

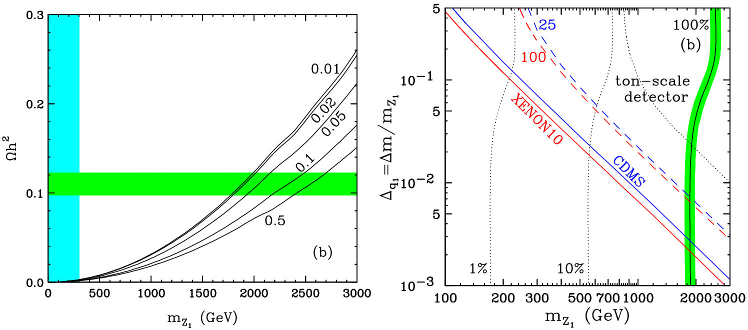
An Application: $W^{3(1)}$ dark matter and neutrinos from the sun

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 Δ_q 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

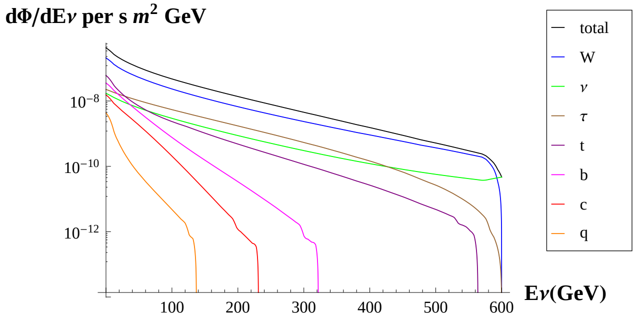
  $\rightarrow$ the annihilation rate is given by the capture rate.
- Amongst the direct or indirect annihilation products are neutrinos which are radiated out of the sun and lead to an excess of the sun's neutrino flux which can be detected by SuperK or ICECUBE.

- 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

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

where

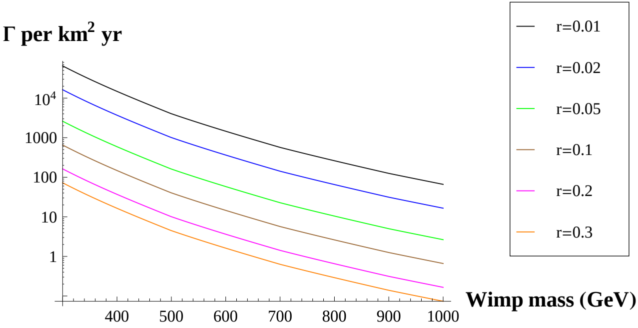
$$r \equiv \frac{m_{q_L^{(1)}} - m_{W^{3(1)}}}{m_{W^{3(1)}}}.$$

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 terms (BLTs).
- BLTs modify the KK spectrum *and* the KK mode couplings.
- BLTs in ED theories imply *tree level* corrections to SM processes.
- 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.
- We presented three sample scenarios

  (“split UED", Higgs LKP UED, and $W^{3(1)}$ LKP UED)
- We presented first (preliminary) results on indirect $W^{3(1)}$ detection.

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.*; Bringmann; ...]
  - Comparison to Wino DM? [Kane *et al.*]