Exploring Universal Extra-Dimensions at the LHC

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory
Problems to be addressed by the underlying theory

- The Nature of Electroweak Symmetry Breaking
- The origin of matter/anti-matter asymmetry
- The origin of Dark Matter
- The problem of hierarchy, fine-tuning, unification with gravity
The Nature of Electroweak Symmetry Breaking

The origin of matter/anti-matter asymmetry

The origin of Dark Matter

The problem of hierarchy, fine-tuning, unification with gravity

The Standard Model
What could lie below the $10^{-19}$m scale?

Extra Dimensions! (ED)
What could lie below the $10^{-19}\text{m}$ scale?

Extra Dimensions! (ED)

Motivations

- String theory, the best candidate to unify gravity & gauge interactions, is only consistent in 10 D space-time
- Extending symmetries:
  - Internal symmetries - GUTs, technicolour...; Fermionic spacetime - SUSY
  - Bosonic spacetime - Extra dimensions
- The presence of XD could have an impact on scales $< M_{\text{planck}}$ (started with ADD)

The question is what is the size and the shape of ED ?!
New perspectives of XD

- The nature of electroweak symmetry breaking
- The origin of fermion mass hierarchies
- The supersymmetry breaking mechanism
- The description of strongly interacting sectors (provide a way to model them)

........
Brief History

- 1914: Nordstrom tried to unify gravity and electromagnetism in 5D $(A_{\mu} \rightarrow A_M$, where $M = 0,1,2,3,4)$

- 1920's: Kaluza and Klein tried using Einstein's equations in 5D $(g^{\mu\nu} \rightarrow g^{MN} \sim g^{\mu\nu}, g^{\mu4}, g^{44})$

- 1970's: Development of superstring theory and supergravity required extra dimensions

- 1998: Arkani-Hamed, Dimopoulos, and Dvali propose Large Extra Dimensions (ADD) as a solution to the Hierarchy /Fine tuning problem of the Standard Model
The idea of ADD

- The Standard Model has been tested to $r \sim 10^{-16}$ mm,
  Gravity has been tested to $r \sim 1$ mm only

Standard Model is localised on the 4D brane
The idea of ADD

- The Standard Model has been tested to $r \sim 10^{-16}$ mm, Gravity has been tested to $r \sim 1$ mm only
- $4D \rightarrow (4 + n)D$

The effective $D = 4$ action is

$$
\frac{M_f^{2+n}}{2} \int d^4x \int_0^{2\pi R} d^m Z \sqrt{G} \, R^{4+n} \rightarrow \frac{1}{2} M_f^{2+n} V_n \int d^4x \sqrt{g} \, R
$$

In case of toroidal compactification of equal radii, $R$

$$
V_n = (2\pi R)^n \quad M_P^2 = M_f^{2+n} V_n
$$
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In case of toroidal compactification of equal radii, $R$

$$V_n = (2\pi R)^n \quad M_P^2 = M_f^{2+n} V_n$$

$r \gg R \Rightarrow$ the torus effectively disappear

$$V(r) = -G_N \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_P^2 r}$$
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$r \ll R \Rightarrow$ observer is able to feel the bulk

$$V(r) = -G_N \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_P^2 r}$$

$$V(r) = -G_* \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_f^{2+n} r^{1+n}}$$
The idea of ADD

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- $4D \rightarrow (4 + n)D$

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$$\frac{M_{f}^{2+n}}{2} \int d^{4}x \int_{0}^{2\pi R} d^{m}Z \sqrt{G} R_{4+n} \rightarrow \frac{1}{2} M_{f}^{2+n} V_{n} \int d^{4}x \sqrt{g} R$$

In case of toroidal compactification of equal radii, $R$

$$V_{n} = (2\pi R)^{n} \quad M_{P}^{2} = M_{f}^{2+n} V_{n}$$

$r \gg R \Rightarrow$ the torus effectively disappear

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Fundamental quantum gravity scale
The current status of ADD

So,

\[ M_P^2 = M_f^{n+2}(2\pi R)^n \]

and respectively,

\[ R = \frac{1}{2\pi} \frac{1}{M_f} \left( \frac{M_P}{M_f} \right)^{\frac{2}{n}} [\text{GeV}^{-1}] \times 0.197[\text{GeV m}] \]
The current status of ADD

So,

\[ M_P^2 = M_f^{n+2}(2\pi R)^n \]

\[ R = \frac{1}{2\pi} \frac{1}{M_f} \left( \frac{M_P}{M_f} \right)^{\frac{2}{n}} \left[ \text{GeV}^{-1} \right] \times 0.197 \left[ \text{GeV m} \right] \]

and respectively,

How big are these dimensions are?

Let us assume \( M_f \sim 1 \text{ TeV} \), then

\[ R \sim \begin{cases} 
10^{15} \text{ mm} & n = 1 \\
1 \text{ mm} & n = 2 \\
10^{-6} \text{ mm} & n = 3 
\end{cases} \]

\[ \times \text{Already ruled out} \]

Collider signature:

\[ pp \rightarrow \text{jet + } E_T \]

The current bound is \( R < 37 \mu \text{m} \)

For \( n = 2 \) this means that \( M > 1.4 \text{ TeV} \)
KK-towers from XD

\[ \Phi(x_\mu, Z) = \Phi(x_\mu, Z + 2\pi R) \]

\[ \mu = 0, 1, 2, 3 \]

Periodicity in Z
KK-towers from XD

Periodicity in $\mathbb{Z}$

$\Phi(x_\mu, Z) = \Phi(x_\mu, Z + 2\pi R)$
$\mu = 0, 1, 2, 3$

Fourier series

$$\Phi(x_\mu, Z) = \sum_{k=0, \pm 1, \ldots} \phi_k(x_\mu) e^{ikZ/R}$$
KK-towers from XD

\[ \Phi(x_\mu, Z) = \Phi(x_\mu, Z + 2\pi R) \]
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Periodicity in Z

Fourier series

\[ \Phi(x_\mu, Z) = \sum_{k=0, \pm 1, \ldots} \phi_k(x_\mu) e^{ikZ/R} \]

The non-zero modes in the KK decomposition

\[ \Box_5 \Phi(x_\mu, Z) \equiv \left( \partial_\mu^2 - \frac{\partial^2}{\partial Z^2} \right) \Phi(x_\mu, Z) = 0 \]

\[ \left( \Box_4 + \frac{k^2}{R^2} \right) \phi_k(x_\mu) \equiv \left( \partial_\mu^2 + \frac{k^2}{R^2} \right) \phi_k(x_\mu) = 0 \]

\[ m_k = \frac{|k|}{R} \]
From Brane - to Bulk: Universal Extra Dimensions (UED)

[Appelquist, Cheng, Dobrescu '01]

• all fields propagate in the extra dimensions, so \( 1/R > 1 \text{ TeV} \) to obey experimental data

• for \( D=5 \) (minimal UED = MUED) we immediately find that \( M_f = 10^{15} \text{ GeV} \) for \( 1/R = 1 \text{TeV} \)

• hierarchy problem is not addressed but MUED has interesting features ...
Minimal Universal Extra Dimensions
compactifying on the circle

\[ \phi(x, y) = \frac{1}{\sqrt{2\pi R}} \phi_0(x) + \sqrt{\frac{\pi}{R}} \sum_{n=1}^{\infty} \left[ \phi_+^n(x) \cos \frac{ny}{R} + \phi_-^n(x) \sin \frac{ny}{R} \right] \]

\[ S = \int d^4x \int_{0}^{2\pi R} dy \frac{1}{2} \left[ \partial_M \phi \partial^M \phi - m^2 \phi(x, y)^2 \right] \]

\[ \mathcal{L}_4 = \frac{1}{2} \left[ \partial_\mu \phi_0 \partial^\mu \phi_0 - m^2 \phi_0^2 \right] + \sum_{n=1}^{\infty} \frac{1}{2} \left[ \partial_\mu \phi_+^n \partial^\mu \phi_+^n - \left( m^2 + \frac{n^2}{R^2} \right) \phi_+^2 \right] \]

- all fields propagate in the bulk - 5D momentum conservation
- This leads to the KK-number conservation

at this point: \( \pm n_1 \pm n_2 = \pm n_3 \)
Universal Extra Dimensions (UED) compactifying on the orbifold

Choose action of $Z_2$ symmetry on Dirac Fermions to project out $\frac{1}{2}$ of them and arranges chirality:

$$\psi_\pm(y) \mapsto \psi'_\pm(-y) = \pm \gamma^5 \psi_\pm(y)$$

If we identify $y \sim -y$ then we require $\psi'_\pm(y) = \psi_\pm(y)$, so

$$\psi_\pm(y) = \psi_0^{R,L} + \sum_n \left( \psi_n^{R,L} \cos n + \psi_n^{L,R} \sin n \right)$$
Universal Extra Dimensions (UED)
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so
$$\psi_\pm(y) = \psi_0^{R,L} + \sum_n \left( \psi_n^{R,L} \cos n + \psi_n^{L,R} \sin n \right)$$

- Translational invariance along the 5th D is broken, but KK parity is preserved!
- KK number $n$ broken down to the KK parity, $(-1)^n$:
  KK excitations must be produced in pairs
- LKP is stable DM candidate!

These vertices are allowed and can be generated at loop-level
Minimal Universal Extra Dimensions

\[ S^1 / \mathbb{Z}_2 \text{ orbifold} \quad \text{SM Gauge group} \quad \text{SM field content} \]

brane localised terms are zero at the cutoff scale
The role of radiative corrections

\[ \sqrt{m_e^2 + \frac{1}{R}^2} < m_e + \frac{1}{R} \] (!!!)

e.g. the 1\textsuperscript{st} KK excitation of the electron is stable at tree-level!

Dark Matter would be charged - which is not acceptable
Loop corrections come from 5D Lorentz violating processes. They appear as tree-level mass corrections in 4D.

- **Bulk corrections:** the gauge bosons receive an extra mass which is KK-independent

\[ \delta m^2_n = \alpha_i \frac{1}{R^2} \]

- **Brane corrections:** \( p_5 \) is not conserved, all particles receive a mass correction

\[ \delta m_n = \beta_i \frac{n}{R} \ln \frac{\Lambda^2}{\mu^2} \quad \text{for fermions} \]

\[ \delta m^2_n = \beta_i \frac{n^2}{R^2} \ln \frac{\Lambda^2}{\mu^2} \quad \text{for bosons} \]

**Problem:** Electroweak symmetry breaking was not included
MUED spectrum at 1loop vs tree-level

$m_H = 120$ GeV, $R^{-1} = 800$ GeV

Tree Level

One Loop

$R^{-1} = 800$ GeV

$\Lambda R$

$M_R$
Our setup

We model the corrections to the self-energy by wave-function normalisations. We replace a 5D-Lorentz conserving action

\[ -\frac{1}{4} F_{MN}^a F^{a MN} + |D_M \Phi|^2 \]

by the following

\[ -\frac{1}{4} F_{\mu \nu}^a F_{\mu \nu}^a + \frac{1}{2} Z \nu F_{\mu 5}^a F_{\mu 5}^a + |D_\mu \Phi|^2 - Z \Phi |D_5 \Phi|^2 \]

which is gauge invariant but not Lorentz covariant. In this way, the fields receive a KK mass

\[ m_n = Z \frac{n}{R} \text{ for fermions} \quad m_n^2 = Z \frac{n^2}{R^2} \text{ for bosons} \]

We are free to match our normalisations with the previous results

\[ Z_i = 1 + \beta_i \ln \frac{\Lambda^2}{\mu^2} \]
Model implementation

• In LanHEP:
LanHEP is a package that generates the Feynman rules out of a Lagrangian.

We have implemented MUED@1L in Feynman and unitary gauges. We
discard the bulk corrections.

• In CalcHEP/CompHEP:
CalcHEP calculates cross-sections out of Feynman rules of a theory. The vertices generated by LanHEP are included into CalcHEP.
We have taken particular care of the splitting of 4-gluon vertices.

Model is available at High Energy Physics Model Database (HEPMDB)
http://hepmdb.soton.ac.uk/hepmdb:1212.0121
Model Validation

Sample of processes with two-gauge bosons for cross-section comparison (in pb) between previous implementation by Datta, Kong, Matchev (DKM) and our implementation (BBMP) arXiv:1212.4858

<table>
<thead>
<tr>
<th>Process</th>
<th>DKM $\sigma$ [pb]</th>
<th>BBMP $\sigma$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (G^{(1)} G^{(1)} \rightarrow G G)</td>
<td>$3.952 \times 10^1$</td>
<td>$3.952 \times 10^1$</td>
</tr>
<tr>
<td>2 (G^{(1)} G \rightarrow G^{(1)} G)</td>
<td>$7.600 \times 10^3$</td>
<td>$7.600 \times 10^3$</td>
</tr>
<tr>
<td>* 3 (G^{(1)} G^{(1)} \rightarrow G^{(1)} G^{(1)})</td>
<td>$8.619 \times 10^3$</td>
<td>$8.600 \times 10^3$</td>
</tr>
<tr>
<td>* 4 (G^{(1)} Z^{(1)} \rightarrow c \bar{c})</td>
<td>$2.132 \times 10^{-1}$</td>
<td>$2.037 \times 10^{-1}$</td>
</tr>
<tr>
<td>* 5 (G^{(1)} \gamma^{(1)} \rightarrow b \bar{b})</td>
<td>$3.651 \times 10^{-2}$</td>
<td>$3.249 \times 10^{-2}$</td>
</tr>
<tr>
<td>* 6 (\gamma^{(1)} \gamma^{(1)} \rightarrow t \bar{t})</td>
<td>$2.641 \times 10^{-2}$</td>
<td>$2.758 \times 10^{-2}$</td>
</tr>
<tr>
<td>* 7 (Z^{(1)} Z^{(1)} \rightarrow d \bar{d})</td>
<td>$9.098 \times 10^{-2}$</td>
<td>$9.165 \times 10^{-2}$</td>
</tr>
<tr>
<td>* 8 (Z^{(1)} Z^{(1)} \rightarrow W^+ W^-)</td>
<td>$9.293 \times 10^0$</td>
<td>$9.288 \times 10^0$</td>
</tr>
<tr>
<td>* 9 (W^{+(1)} W^{-(1)} \rightarrow Z Z)</td>
<td>$2.744 \times 10^0$</td>
<td>$2.761 \times 10^0$</td>
</tr>
<tr>
<td>10 (W^{+(1)} W^{-(1)} \rightarrow Z \gamma)</td>
<td>$1.653 \times 10^0$</td>
<td>$1.653 \times 10^0$</td>
</tr>
<tr>
<td>*11 (W^{+(1)} W^{-(1)} \rightarrow W^+ W^-)</td>
<td>$3.152 \times 10^0$</td>
<td>$3.081 \times 10^0$</td>
</tr>
</tbody>
</table>

\(\sqrt{s}=2\) TeV  \(P_T > 100\) GeV

KK up to n=2: if KK numbers of the external particles is 5 or less \(<2*(n+1)\) in general] gauge invariance is ensured
Model Validation

Proper implementation of the Higgs sector lead to the correct High Energy asymptotic which respects Unitarity
EW precision constraints

The tower of KK particles modify the gauge bosons self-energies, contributing to the S, T, and U electroweak parameters:

\[
S = \frac{4 \sin^2 \theta_W}{\alpha} \left[ \frac{3g^2}{4(4\pi)^2} \left( \frac{2}{9} M_{KK}^2 \right) \zeta(2) + \frac{g^2}{4(4\pi)^2} \left( \frac{1}{6} M_H^2 \right) \zeta(2) \right],
\]

\[
T = \frac{1}{\alpha} \left[ \frac{3g^2}{2(4\pi)^2} \frac{m_t^2}{M_W^2} \left( \frac{2}{3} M_{KK}^2 \right) \zeta(2) + \frac{g^2 \sin^2 \theta_W}{(4\pi)^2 \cos^2 \theta_W} \left( \frac{5}{12} M_H^2 \right) \zeta(2) \right],
\]

\[
U = -\frac{4 \sin^2 \theta_W}{\alpha} \left[ \frac{g^2 \sin^2 \theta_W}{(4\pi)^2} \frac{M_W^2}{M_{KK}^2} \left( \frac{1}{6} \zeta(2) - \frac{1}{15} M_H^2 \zeta(4) \right) \right],
\]

G fitter

arXiv: 1107.0975

68%, 95%, 99% CL fit contours (allowed)
**FCNC and DM constraints**

**FCNC**

KK modes will give contributions to FCNC processes. From $b \rightarrow s \gamma$

$1/R > 600$ GeV

**Cosmology (DM)**

The evaluation of the LKP relic abundance depends on the spectrum details and on the number of KK levels included in the calculation (e.g., level 2 resonances, level 2 particles in the final state, etc). Electroweak symmetry breaking effects are also important.

*Matsumoto, Senami '05; Kong, Matchev '05
Brunel, Kribs '05; Belanger, Kakizaki, Pukhov '10
............

WMAP imposes a bound from above to DM scale: if DM were heavier it would lead to the Universe having a measurable positive curvature

$1/R < 1.6$ TeV
The role of the 2\textsuperscript{nd} level of KK excitation

Processes important for calculating DM relic abundance...

Self-annihilation

\[ \gamma^{(1)} \]

\[ H, H^{(2)} \]

\[ \gamma^{(1)}, \text{SM} \]

\[ f \]

\[ f^{(1)} \]

\[ \gamma^{(1)} \]

\[ \gamma^{(1)}, \text{SM} \]

\[ \gamma^{(1)} \]

\[ \gamma^{(1)} \]

\[ \gamma^{(1)} \]

\[ \gamma^{(1)} \]

Co-annihilation

\[ \gamma^{(1)} \]

\[ e^{(1)} \]

\[ e \]

\[ \gamma^{(1)} \]

\[ e^{(1)} \]

\[ e \]

\[ \gamma \]

\[ e^{(1)} \]

\[ t \]

\[ \gamma^{(1)} \]

\[ e^{(2)} \]

\[ e \]

\[ \gamma^{(2)} \]
The role of the 2\textsuperscript{nd} level of KK excitation

Belanger et al. 2010
The role of the Higgs searches in constraining of the mUED model

- Production is enhanced
- Decay is slightly suppressed

AB, Belanger, Brown, Kakizaki, Pukhov '12
Constraints from the Higgs data

- Production is enhanced
- Decay is slightly suppressed
- Overall, the $GG \rightarrow H \rightarrow \gamma\gamma$ is enhanced

AB, Belanger, Brown, Kakizaki, Pukhov '12
Same channels ($\gamma\gamma$ and $WW$) from CMS/ATLAS are combined
$R^{-1} < 500$ is excluded at 95% CL
overall, the $GG \rightarrow H \rightarrow \gamma\gamma$ is enhanced
Narrow window around 125 GeV is left

AB, Belanger, Brown, Kakizaki, Pukhov '12
The Status of MUED (with LHC@7 TeV Higgs data)
Data Fit with MUED vs SM

ATLAS Preliminary

W, Z H → bb
\[ \bar{y}_S = 7 \text{ TeV}, \quad L_{\text{int}} = 4.7 \text{ fb}^{-1} \]
\[ y_S = 8 \text{ TeV}, \quad L_{\text{int}} = 13 \text{ fb}^{-1} \]

H → ττ
\[ \bar{y}_S = 7 \text{ TeV}, \quad L_{\text{int}} = 4.6 \text{ fb}^{-1} \]
\[ y_S = 8 \text{ TeV}, \quad L_{\text{int}} = 13 \text{ fb}^{-1} \]

H → WW(\* → h\*h
\[ \bar{y}_S = 7 \text{ TeV}, \quad L_{\text{int}} = 4.6 \text{ fb}^{-1} \]
\[ y_S = 8 \text{ TeV}, \quad L_{\text{int}} = 13 \text{ fb}^{-1} \]

H → γγ
\[ \bar{y}_S = 7 \text{ TeV}, \quad L_{\text{int}} = 4.8 \text{ fb}^{-1} \]
\[ y_S = 8 \text{ TeV}, \quad L_{\text{int}} = 13 \text{ fb}^{-1} \]

H → ZZ(\* → 4l
\[ \bar{y}_S = 7 \text{ TeV}, \quad L_{\text{int}} = 4.6 \text{ fb}^{-1} \]
\[ y_S = 8 \text{ TeV}, \quad L_{\text{int}} = 13 \text{ fb}^{-1} \]

Combined
\[ \bar{y}_S = 7 \text{ TeV}, \quad L_{\text{int}} = 4.6 - 4.8 \text{ fb}^{-1} \]
\[ y_S = 8 \text{ TeV}, \quad L_{\text{int}} = 13 \text{ fb}^{-1} \]

μ = 1.35 ± 0.24

CMS Preliminary

m_H = 125.7 GeV

p_{SM} = 0.94

Best fit \( \sigma/\sigma_{SM} \)

Excluded at 95% CL

\[ \chi^2 \]

Signal strength (μ)

\[ R^{-1} \text{ (GeV)} \]

SM

MUED
There is no hint on MUED from the Higgs data ... 
The fit of the SM if perfect :-(
The fit of MUED does not improve \( \chi^2 \)
mUED: the mass spectrum defines dominant decay pattern to leptons!!!
mUED: the mass spectrum defines dominant decay pattern to leptons!!!
mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12

Q¹ Q¹ production rate is the highest
mUED collider phenomenology with leptons

Lepton multiplicity:

Signal vs BG before (left) and after(right) selection cuts

\[
\begin{align*}
P_T^{\ell_1} &> 20 \text{ GeV}, \quad P_T^{\ell_2}\text{(all)} > 10 \text{ GeV}, \quad |\eta_{\ell}| < 2.5, \quad \Delta R_{\ell j} = \sqrt{\Delta \phi_{\ell j}^2 + \Delta \eta_{\ell j}^2} > 0.5 \\
|m_Z - M_{\ell\ell}| &> 10 \text{ GeV} \\
P_T &> 50 \text{ GeV} \\
P_T^{\ell_1} &< 100 \text{ GeV}; \quad P_T^{\ell_2} < 70 \text{ GeV}; \quad P_T^{\ell_3} < 50 \text{ GeV} \\
M_{\text{eff}} &> R^{-1}/5 \quad M_{\text{eff}} = P_T + \sum_{\ell,j} P_T
\end{align*}
\]
mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau’12

Cut on the maximum $P_T$ of the lepton is important!

$mUED$ Signal vs Background @LHC, $\sqrt{s} = 8$ TeV

3-lepton signature has the highest significance in comparison with 4-lepton signature
mUED collider phenomenology with leptons

- Small mass gap (as compared to MSSM) – much lower missing PT
- Quite a few PHENO papers, but there are no experimental limits!!!
  the projected limit from this study: $R^{-1} > 1.2–1.3$ TeV
- 3-lepton signature – is very promising:
  LHC@14 will eventually discover or close MUED!
Constraints from di-lepton searches

Edelhäuser, Flacke, Kramer, '13

- Production

- Decay

Lower bounds

<table>
<thead>
<tr>
<th>$\Lambda R$</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^{-1}/[\text{GeV}]$</td>
<td>623</td>
<td>613</td>
<td>601</td>
<td>627</td>
</tr>
</tbody>
</table>
Vacuum stability bounds

\[ \frac{\Lambda_{\text{max}}}{M_{KK}} \]

\[ M_{KK} \text{ (GeV)} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>mUED</th>
<th>( T^2/Z_2 )</th>
<th>( T^2/(Z_2 \times Z'_2) )</th>
<th>( T^2/Z_4 )</th>
<th>( S^2 )</th>
<th>( S^2/Z_2 )</th>
<th>( RP^2 )</th>
<th>( PS^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_{\text{max}} )</td>
<td>5.0</td>
<td>2.5</td>
<td>2.9</td>
<td>3.4</td>
<td>2.3</td>
<td>3.2</td>
<td>2.3</td>
<td>1.9</td>
</tr>
</tbody>
</table>
**6D UED**  
(Dark Matter in a twisted bottle)  
Arbey, Cacciapaglia, Deandrea, Kubik '12

### Spectrum of the SM

<table>
<thead>
<tr>
<th>$pKK = (-1)^{k+1}$</th>
<th>(0,0) $m = 0$</th>
<th>(1,0) &amp; (0,1) $m = 1$</th>
<th>(1,1) $m = 1.41$</th>
<th>(2,0) &amp; (0,2) $m = 2$</th>
<th>(2,1) &amp; (1,2) $m = 2.24$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge bosons G, A, Z, W</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gauge scalars G, A, Z, W</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>Higgs boson(s)</td>
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<td>✓</td>
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<tr>
<td>Fermions</td>
<td>✓</td>
<td>✓</td>
<td>✓ (x2)</td>
<td>✓</td>
<td>✓ (x2)</td>
</tr>
</tbody>
</table>

DM candidate here!
6D UED DM bounds

Arbey, Cacciapaglia, Deandrea, Kubik’12

DM relic abundance bounds

Asymmetric

Symmetric

two tiers contribute to the relic abundance!

$R^5 > R^6$

$R^5 = R^6$

DM direct detection bounds

Excluded!

Xenon2011

Excluded!
6D UED LHC bounds

“composition” of signal signatures

MHT-HT analysis plane

Exclusion limit: $M_{KK} > 600-700$ GeV
Almost all parameter space is excluded
Conclusions

• UED are limited from above by DM relic abundance and from below by the LHC searches.
LHC and DM search experiments provide an important test: LHC@14 TeV will discover or exclude the complete parameter space for 5 & 6D UED (no boundary localised terms).

• There are still no dedicated experimental searches for MUED signals which could be in data! It is time to check them! 3-lepton signal is very promising for MUED at the LHC.

• Consistent MUED with EWSB and loop-corrections is implemented into LanHEP and publicly available at HEPMDB [CalcHEP and UFO(Madgraph5) formats are available]. It is ready to be used by experimentalists and theorists!
THANK YOU!
mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12

Signal vs BG in lepton multiplicity
Backup slides

\[ R^{-1} = 1500 \text{ GeV} \]
\[ m_H = 125 \text{ GeV} \]
Figure 5: Rescaled LKP-nucleon cross section on $Ge^{76}$ vs $m_{LKP}$ for $m_{h} = 120$ GeV, $\Lambda R = 20$ and 2 sets of quark coefficients ($\sigma_{\pi N}, \sigma_{0}$) = (56 MeV, 35 MeV) (dash) or (47 MeV, 42.9 MeV) (dot) and for different values of the mass splitting between the KK singlet d-quarks and the LKP including the MUED case (left panel). The MUED results for $m_{h} = 220$ GeV are also shown. In each line the region between the blobs is consistent with the 3$\sigma$ WMAP range. Rescaled LKP-nucleon cross section on $Ge^{76}$ vs $m_{h}$ for $R^{-1} = 1300$ GeV, $\Lambda R = 20$ (right). In each line the region left of the blob is consistent with the 3$\sigma$ WMAP range.
The spectrum

Because of the loop-corrections, the $B$ and $W^3$ do not mix with the Weinberg angle

$$
\begin{pmatrix}
Z_B \frac{n^2}{R^2} + \frac{1}{4} g_1^2 v^2 & -\frac{1}{4} g_1 g_2 v^2 \\
-\frac{1}{4} g_1 g_2 v^2 & Z_W \frac{n^2}{R^2} + \frac{1}{4} g_2^2 v^2
\end{pmatrix}
$$

Consequently, the mass eigenstates are not the KK photon or KK Z-boson. We call them $P^{(n)}$ and $Q^{(n)}$.

There is a tree-level $H^{(k)} P^{(l)} P^{(m)}$ vertex.

Associated with the KK vectors $A^{(n)}_\mu$, the Goldstone bosons are combinations of the fifth components $A^{(n)}_5$ and the Higgses $\chi^{(n)}$.

Finally, there are two KK fermions per SM one, and they mix with angles related to the $Z_i$. 
## The spectrum

<table>
<thead>
<tr>
<th>Spin</th>
<th>Name</th>
<th>Particle</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gluon</td>
<td>$G^{(n)}$</td>
<td>$m_{G}^{2}(n) = Z_{G} \frac{n^{2}}{R^{2}}$</td>
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<tr>
<td></td>
<td>$P$ boson</td>
<td>$P^{(n)}$</td>
<td>$m_{P}^{2}(n)$</td>
</tr>
<tr>
<td></td>
<td>$Q$ boson</td>
<td>$Q^{(n)}$</td>
<td>$m_{Q}^{2}(n)$</td>
</tr>
<tr>
<td></td>
<td>$W$ boson</td>
<td>$W^{\pm}(n)$</td>
<td>$m_{W}^{2}(n) = Z_{W} \frac{n^{2}}{R^{2}} + M_{W}^{2}$</td>
</tr>
<tr>
<td>1/2</td>
<td>Neutrinos</td>
<td>Neutrinos</td>
<td>Masses of neutrinos</td>
</tr>
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<td></td>
<td>Charged leptons 1</td>
<td>$\nu_{e}^{(n)}$</td>
<td>$m_{\nu_{e}}^{2}(n) = Z_{eL} \frac{n}{R}$</td>
</tr>
<tr>
<td></td>
<td>$e_{1}^{(n)}$, $\nu_{1}^{(n)}$, $\tau_{1}^{(n)}$</td>
<td>$m_{e}$, $m_{\tau}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charged leptons 2</td>
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<td>$m_{e}$, $m_{\tau}$</td>
</tr>
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<td>Up-quarks 1</td>
<td>$u_{1}^{(n)}$, $c_{1}^{(n)}$, $t_{1}^{(n)}$</td>
<td>$m_{u}$, $m_{c}$, $m_{t}$</td>
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<td>Up-quarks 2</td>
<td>$u_{2}^{(n)}$, $c_{2}^{(n)}$, $t_{2}^{(n)}$</td>
<td>$m_{u}$, $m_{c}$, $m_{t}$</td>
</tr>
<tr>
<td></td>
<td>Down-quarks 1</td>
<td>$d_{1}^{(n)}$, $s_{1}^{(n)}$, $b_{1}^{(n)}$</td>
<td>$m_{d}$, $m_{s}$, $m_{b}$</td>
</tr>
<tr>
<td></td>
<td>Down-quarks 2</td>
<td>$d_{2}^{(n)}$, $s_{2}^{(n)}$, $b_{2}^{(n)}$</td>
<td>$m_{d}$, $m_{s}$, $m_{b}$</td>
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<tr>
<td>0</td>
<td>Higgs scalar</td>
<td>$h^{(n)}$</td>
<td>$m_{h}^{2}(n) = Z_{H} \frac{n^{2}}{R^{2}}$</td>
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<tr>
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<td>neutral scalar</td>
<td>$a_{0}^{(n)}$</td>
<td>$m_{a_{0}}^{2}(n) = Z_{H} \left[ \frac{n}{R} + \frac{v^{2}}{4} \left( \frac{g_{1}^{2}}{Z_{B}} + \frac{g_{2}^{2}}{Z_{W}} \right) \right]$</td>
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<td>charged scalar</td>
<td>$a_{\pm}^{(n)}$</td>
<td>$m_{a_{\pm}}^{2}(n) = \frac{Z_{H}}{Z_{W}} \left[ Z_{W} \frac{n^{2}}{R^{2}} + M_{W}^{2} \right]$</td>
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