(Flat) Extra Dimensions: Where Do We Stand?

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High Energy Physics Seminar
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SUSY Searches

Summary of CMS SUSY Results* in SMS framework

For decays with intermediate mass, 
\[ m_{\text{intermediate}} = x m_{\text{mother}} - (1-x) m_{\text{LSP}} \]

For decays with intermediate mass, 
\[ m_{\text{intermediate}} = x m_{\text{mother}} - (1-x) m_{\text{LSP}} \]

CMS Preliminary

m(mother)-m(LSP)=200 GeV

SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.96 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
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SUS-11-011 L=4.98 /fb
SUS-13-011 L=19.5 /fb

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit

Mass scales [GeV]
### ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** SUSY 2013

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>e, μ, τ, γ Jets</th>
<th>E^{miss} T</th>
<th>$\int L dt$ (fb$^{-1}$)</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>1 e, μ</td>
<td>3-6 jets</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0</td>
<td>7-10 jets</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0</td>
<td>7-10 jets</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>GMSB (L NLSP)</td>
<td>0</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.7</td>
</tr>
<tr>
<td>GMSB (L NLSP)</td>
<td>1-2</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.7</td>
</tr>
<tr>
<td>GMSB (L NLSP)</td>
<td>2 γ</td>
<td>-</td>
<td>Yes</td>
<td>4.8</td>
</tr>
<tr>
<td>GMS (bino NLSP)</td>
<td>1 e, μ + γ</td>
<td>-</td>
<td>Yes</td>
<td>4.8</td>
</tr>
<tr>
<td>GMS (bino NLSP)</td>
<td>1 e, μ + γ</td>
<td>-</td>
<td>Yes</td>
<td>4.8</td>
</tr>
<tr>
<td>GMS (bino NLSP)</td>
<td>2 e, μ (Z)</td>
<td>0-3 jets</td>
<td>Yes</td>
<td>5.8</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0</td>
<td>mono-jet</td>
<td>Yes</td>
<td>10.5</td>
</tr>
<tr>
<td>$g \rightarrow b\bar{b}$</td>
<td>0</td>
<td>3 b</td>
<td>Yes</td>
<td>20.1</td>
</tr>
<tr>
<td>$g \rightarrow t\bar{b}$</td>
<td>0</td>
<td>7-10 jets</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>$g \rightarrow t\bar{t}$</td>
<td>0-1 e, μ</td>
<td>3 b</td>
<td>Yes</td>
<td>20.1</td>
</tr>
<tr>
<td>$g \rightarrow b\bar{b}$</td>
<td>0</td>
<td>3 b</td>
<td>Yes</td>
<td>20.1</td>
</tr>
<tr>
<td>$g \rightarrow t\bar{b}$</td>
<td>0-1 e, μ</td>
<td>3 b</td>
<td>Yes</td>
<td>20.1</td>
</tr>
</tbody>
</table>

### 3rd gen. squarks direct production

| b_2 b_1, b_1 b_1 + b_1 b_1 | 0              | 2 b        | Yes                      | 20.3        |
| b_2 b_2, b_2 b_1 + b_1 b_2 | 2 e, μ (SS)    | 0-3 b      | Yes                      | 20.7        |
| f_1 (light), f_1 \rightarrow b_1 b_1 | 1-2 e, μ      | 1-2 b      | Yes                      | 4.7         |
| f_1 (light), f_1 \rightarrow b_1 b_1 | 2 e, μ + γ    | 0-2 jets   | Yes                      | 20.3        |
| f_1 (light), f_1 \rightarrow b_2 b_2 | 1 e, μ        | 1 b        | Yes                      | 20.7        |
| f_1 (light), f_1 \rightarrow b_2 b_2 | 1 e, μ + γ    | 1 b        | Yes                      | 20.7        |
| f_1 (heavy), f_1 \rightarrow t_1 t_1 | 0              | 2 b        | Yes                      | 20.1        |
| f_1 (heavy), f_1 \rightarrow t_1 t_1 | 2 e, μ + γ    | 0-2 jets   | Yes                      | 20.3        |
| f_1 (natural GMSB)        | 2 e, μ (Z)    | 1 b        | Yes                      | 20.7        |
| f_2, f_2, f_1 + f_1 + Z   | 3 e, μ (Z)    | 1 b        | Yes                      | 20.7        |

### EW direct

| $\tilde{t}_L \tilde{q}_R$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{t}_R$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{q}_L$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{q}_R$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{t}_R$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{q}_L$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{q}_R$ | 2 e, μ      | 0          | Yes                      | 20.3        |
| $\tilde{t}_L \tilde{t}_R$ | 2 e, μ      | 0          | Yes                      | 20.3        |

### Long-lived sparticles

| Direct $\tilde{t}_1 \tilde{t}_1$ prod., long-lived $\tilde{t}_1$ | 1 jet | Yes | 20.3 |
| Direct $\tilde{t}_1 \tilde{t}_1$ prod., long-lived $\tilde{t}_1$ | 1 jet | Yes | 20.3 |
| Disapp. trk $\tilde{t}_1 \tilde{t}_1$ | 1 jet | Yes | 20.3 |

### RPV

| LPV $\tilde{q}_R \tilde{q}_L$, $\tilde{q}_L \rightarrow t_1 t_1$ | 1 μ, e, μ + γ | 1 b | Yes | 20.3 |
| LPV $\tilde{t}_L \tilde{q}_R$, $\tilde{t}_L \rightarrow t_1 t_1$ | 1 μ, e, μ + γ | 1 b | Yes | 20.3 |
| LPV $\tilde{t}_L \tilde{q}_L$, $\tilde{t}_L \rightarrow t_1 t_1$ | 1 μ, e, μ + γ | 1 b | Yes | 20.3 |

### Other

| Gluon pair, gluon - $g\rightarrow q\bar{q}$ | 0 | 4 jets | Yes | 20.3 |
| Gluon pair, gluon - $g\rightarrow t\bar{t}$ | 2 e, μ (SS) | 1 b | Yes | 14.3 |

### Mass scale [TeV]

<table>
<thead>
<tr>
<th>Mass scale</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>ATLAS-CONF-2013-051</td>
</tr>
<tr>
<td>8 TeV</td>
<td>ATLAS-CONF-2013-052</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
Why SUSY is not there?

- Perhaps SUSY scale is higher than we thought
  - but there are no 2-3 sigma indications at all
- How to hide (?):
  - make spectrum more degenerate
  - make SUSY scale higher and higher (and higher …)
  - we haven’t really looked at every single channel;
    - find exotic productions / decays
  - introduce more parameters;
    - weaken current bounds
Non-SUSY Searches

### ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)

<table>
<thead>
<tr>
<th>ATLAS Preliminary</th>
<th>Non-SUSY Searches</th>
<th>ATLAS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L dt = (1 - 20) fb^{-1}$</td>
<td><strong>$\mathcal{L} = 7, 8$ TeV</strong></td>
<td>$\mathcal{L} = 7, 8$ TeV</td>
</tr>
<tr>
<td>$f_S = 7, 8$ TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda$ (constructive int.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda$ (C=1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda$ (isospin doublet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda$ (isospin singlet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda$ (charge -1/3, coupling $\kappa_{\mathcal{Q}} = v/m_H$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Extra dimensions

<table>
<thead>
<tr>
<th>Large ED (ADD)</th>
<th>monojet + $E_{T,\text{miss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large ED (ADD)</td>
<td>monophoton + $E_{T,\text{miss}}$</td>
</tr>
<tr>
<td>Large ED (ADD)</td>
<td>diphoton &amp; dilepton, $m_{T_{\text{miss}}}$</td>
</tr>
<tr>
<td>UED</td>
<td>diphoton + $E_{T,\text{miss}}$</td>
</tr>
<tr>
<td>S'Z ED</td>
<td>dilepton, $m_{T_{\text{miss}}}$</td>
</tr>
<tr>
<td>RS1</td>
<td>dilepton, $m_{T_{\text{miss}}}$</td>
</tr>
<tr>
<td>RS1</td>
<td>WW resonance, $m_{T_{\text{miss}}}$</td>
</tr>
<tr>
<td>Bulk RS</td>
<td>ZZ resonance, $m_{T_{\text{miss}}}$</td>
</tr>
</tbody>
</table>

### Cl

| RS q̄q → tf (BR=0.925) | $\Lambda$-jets, $m_{T_{\text{miss}}}$ |
| ADD BH ($M_{T_{\text{th}}}/M_{\Lambda} = 3$) | SM di-muon, N_{had. part.} |
| ADD BH ($M_{T_{\text{th}}}/M_{\Lambda} = 3$) | leptons + jets, $Z_2$ |

### V

| Quantum black hole: dijet, $F_{\text{miss}}$ |
| Other possible: dijet, $F_{\text{miss}}$ |

### LQ

| Scalar LQ pair ($\beta$'s$^1$) | kin. vars. in eejj, eejjj |
| Scalar LQ pair ($\beta$'s$^1$) | kin. vars. in uut, uutjj, uutjj |

### New quarks

| 4th generation: $b'^- \to s$ dilepton + jets + $E_{T,\text{miss}}$ |
| Vector-like quark: $T \to H^+\chi$ |
| Vector-like quark: $C \circ m_{T_{\text{miss}}}$ |

### Other

| Heavy lepton $N^\pm$ (type III seesaw) | $Z$-jets, $m_{T_{\text{miss}}}$ |
| Heavy lepton $H^\pm$ (DY prod., BR=$H^\pm$-ll=1) | SS ee (ee), $m_{T_{\text{miss}}}$ |
| Color octet scalar: dijet resonance, $m_{T_{\text{miss}}}$ |
| Multi-charged particles (DY prod.) | highly ionizing tracks |
| Magnetic monopoles (DY prod.) | highly ionizing tracks |

### Mass scale [TeV]

<table>
<thead>
<tr>
<th>10^{-1}</th>
<th>1</th>
<th>10</th>
<th>10^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.17 TeV</td>
<td>1.93 TeV</td>
<td>4.18 TeV</td>
<td>4.71 TeV</td>
</tr>
<tr>
<td>4.47 TeV</td>
<td>1.40 TeV</td>
<td>2.47 TeV</td>
<td>7.6 TeV</td>
</tr>
<tr>
<td>4.7 TeV</td>
<td>1.23 TeV</td>
<td>4.11 TeV</td>
<td>13.9 TeV</td>
</tr>
<tr>
<td>4.9 TeV</td>
<td>1.02 TeV</td>
<td>5.05 TeV</td>
<td>23.4 TeV</td>
</tr>
<tr>
<td>5.1 TeV</td>
<td>0.82 TeV</td>
<td>6.13 TeV</td>
<td>32.9 TeV</td>
</tr>
<tr>
<td>5.3 TeV</td>
<td>0.62 TeV</td>
<td>7.21 TeV</td>
<td>42.4 TeV</td>
</tr>
<tr>
<td>5.5 TeV</td>
<td>0.42 TeV</td>
<td>8.29 TeV</td>
<td>51.9 TeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena shown.
• What are current LHC bounds on (flat) ED?
• Is KK-photon dark matter ruled out?
• Is Universal Extra Dimensions still alive?
• My response was:
  • Why do you ask me?
  • I am not in CMS or ALTAS collaboration
  • I did not make these models anyway
  • I am working on something different these days…
Short Answers

• MH=126 GeV and relic abundance disfavors 2UED (6D) with minimal mass spectrum
• MUED (5D) is very constrained as any other models
  • $R_{\text{inv}} > 1.2-1.3$ TeV from tri-lepton search (8 TeV)
  • $R_{\text{inv}} < 1.5$ TeV from relic abundance
• There are ways to introduces more parameters
  • brane-localized terms and fermion-bulk masses
• MUED exists in various event generators: CalcHEP, PYTHIA, MG/ME, Herwig, Sherpa, etc
• For NMUED, coupling and mass spectrum can be modified
Outline

• Universal Extra Dimensions (TeV⁻¹ ED)
  • basic review
  • collider and dark matter
  • 5D and 6D
  • current LHC bounds (2012)
• Beyond Minimal Model (2013-2014)
  • more parameters
  • AMS-02 data (positrons)
  • exotic signatures?
• (no gravity in this talk)
If there are extra dimensions...

- Energy-momentum relation in 5D.

\[
E^2 = p_{x_1}^2 + p_{x_2}^2 + p_{x_3}^2 + m^2 \quad E^2 = p_{x_1}^2 + p_{x_2}^2 + p_{x_3}^2 + p_y^2 + m^2
\]

- If an extra dimension is a circle,

\[
p_y = \frac{2\pi}{\lambda} \quad \lambda = \frac{2\pi R}{n} \Rightarrow p_y = \frac{2\pi n}{2\pi R} = \frac{n}{R}
\]

\[
E^2 = p_{x_1}^2 + p_{x_2}^2 + p_{x_3}^2 + \frac{n^2}{R^2} + m^2 \equiv \tilde{p}^2 + M_n^2 \quad M_n = \sqrt{\frac{n^2}{R^2} + m^2}
\]
A Scalar Field in 5 Dimensions

• Action for a scalar of mass $m$

$$S = \int d^4x dy \left[ \partial_M \Phi^*(x, y) \partial^M \Phi(x, y) - m^2 \Phi^*(x, y) \Phi(x, y) \right]$$

$M, N = 0, 1, 2, 3, 5 \equiv \mu, 5,
\quad g_{\mu\nu} = (+ - - - -)
\quad \partial_{\mu} = (\partial_{\mu}, \partial_5)$

• ASSUME an extra dimension is a circle $(S_1)$,

$$\Phi(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{\infty} \phi_n(x) \exp \left( \frac{iny}{R} \right) \quad 2\pi R \delta_{n,m} = \int_0^{2\pi R} dy \exp \left( \frac{i(n-m)y}{R} \right)$$

• Compactify ED (integrate out unknown coordinate)

$$S = \sum_{n=-\infty}^{\infty} \int d^4x \left[ \partial_\mu \phi_n^*(x) \partial^\mu \phi_n(x) - \left( \frac{n^2}{R^2} + m^2 \right) \phi_n^*(x) \phi_n(x) \right] \quad m_n = \sqrt{\frac{n^2}{R^2} + m^2}.$$
Problems with circular ED

- No (two components) chiral fermions in $D > 4$.
- $SO(1,3) \sim SU(2) \times SU(2) \sim SO(3) \times SO(3)$
- Each gauge field has 5 components, $(G_{\mu}(x, y), G_5(x, y))$
- What particle corresponds to this 5-th component?
- Introduce “Orbifold” (manifold with fixed points)
A Scalar Field on an Interval

- Action for a scalar with potential $V$
  \[ S_{\text{bulk}} = \int d^4x \int_0^{\pi R} \left( \frac{1}{2} \partial^M \phi \partial_M \phi - V(\phi) \right) dy \]

- Variational principle leads to $\delta S = 0$
  \[ \delta S = \int d^4x \int_0^{\pi R} \left( \partial^M \phi \partial_M \delta \phi - \frac{\partial V}{\partial \phi} \delta \phi \right) dy \]
  \[ \delta S = \int d^4x \int_0^{\pi R} dy \left[ -\partial_\mu \partial^\mu \phi \delta \phi - \frac{\partial V}{\partial \phi} \delta \phi - \partial_y \phi \partial_y \delta \phi \right] \]

- Keep the boundary terms when integrating by parts
  \[ \delta S = \int d^4x \int_0^{\pi R} \left[ -\partial_M \partial^M \phi - \frac{\partial V}{\partial \phi} \right] \delta \phi - \left[ \int d^4x \partial_y \phi \delta \phi \right]_0^{\pi R} \]

- Bulk EOM and boundary terms
  \[ \partial_M \partial^M \phi = -\frac{\partial V}{\partial \phi} \quad \text{Neumann BC } \partial_y \phi| = 0 \]
  \[ H(x, y) = \frac{1}{\sqrt{\pi R}} \left\{ H(x) + \sqrt{2} \sum_{n=1}^{\infty} H_n(x) \cos \left(\frac{ny}{R}\right) \right\} \]
Standard Model on $S_1/Z_2$

\[ \mathcal{L}_{Gauge} = \frac{1}{2} \int_{-\pi R}^{\pi R} dy \left\{ -\frac{1}{4} B_{MN} B^{MN} - \frac{1}{4} W^a_{MN} W^{aMN} - \frac{1}{4} G^A_{MN} G^{AMN} \right\}, \]

\[ \mathcal{L}_{GF} = \frac{1}{2} \int_{-\pi R}^{\pi R} dy \left\{ -\frac{1}{2\xi} \left( \partial^\mu B_\mu - \xi \partial_5 B_5 \right)^2 - \frac{1}{2\xi} \left( \partial^\mu W^a_\mu - \xi \partial_5 W^a_5 \right)^2 
\quad \quad \quad \quad \quad \quad - \frac{1}{2\xi} \left( \partial^\mu G^A_\mu - \xi \partial_5 G^G_5 \right)^2 \right\}, \]

\[ \mathcal{L}_{Leptons} = \frac{1}{2} \int_{-\pi R}^{\pi R} dy \left\{ i \bar{L}(x,y) \Gamma^M D_M L(x,y) + i \bar{E}(x,y) \Gamma^M D_M E(x,y) \right\}, \]

\[ \mathcal{L}_{Quarks} = \frac{1}{2} \int_{-\pi R}^{\pi R} dy \left\{ i \bar{Q}(x,y) \Gamma^M D_M Q(x,y) + i \bar{U}(x,y) \Gamma^M D_M U(x,y) \right\}, \]

\[ \mathcal{L}_{Yukawa} = \frac{1}{2} \int_{-\pi R}^{\pi R} dy \left\{ \lambda_u \bar{Q}(x,y) U(x,y) i \tau^2 H^*(x,y) + \lambda_d \bar{Q}(x,y) D(x,y) H(x,y) \right\}, \]

\[ \mathcal{L}_{Higgs} = \frac{1}{2} \int_{-\pi R}^{\pi R} dy \left[ (D_M H(x,y))^\dagger (D^M H(x,y)) + \mu^2 H^\dagger(x,y) H(x,y) 
\quad \quad \quad \quad \quad \quad - \lambda (H^\dagger(x,y) H(x,y))^2 \right], \]
\begin{align*}
H(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ H(x) + \sqrt{2} \sum_{n=1}^{\infty} H_n(x) \cos\left(\frac{ny}{R}\right) \right\}, \\
B_\mu(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ B_\mu^0(x) + \sqrt{2} \sum_{n=1}^{\infty} B_\mu^n(x) \cos\left(\frac{ny}{R}\right) \right\}, \\
B_5(x, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} B_5^n(x) \sin\left(\frac{ny}{R}\right), \\
W_\mu(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ W_\mu^0(x) + \sqrt{2} \sum_{n=1}^{\infty} W_\mu^n(x) \cos\left(\frac{ny}{R}\right) \right\}, \\
W_5(x, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} W_5^n(x) \sin\left(\frac{ny}{R}\right), \\
G_\mu(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ G_\mu^0(x) + \sqrt{2} \sum_{n=1}^{\infty} G_\mu^n(x) \cos\left(\frac{ny}{R}\right) \right\}, \\
G_5(x, y) &= \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} G_5^n(x) \sin\left(\frac{ny}{R}\right), \\
Q(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ q_L(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[ P_L Q_L^n(x) \cos\left(\frac{ny}{R}\right) + P_R Q_R^n(x) \sin\left(\frac{ny}{R}\right) \right] \right\}, \\
U(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ u_R(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[ P_R u_R^n(x) \cos\left(\frac{ny}{R}\right) + P_L u_L^n(x) \sin\left(\frac{ny}{R}\right) \right] \right\}, \\
D(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ d_R(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[ P_R d_R^n(x) \cos\left(\frac{ny}{R}\right) + P_L d_L^n(x) \sin\left(\frac{ny}{R}\right) \right] \right\}, \\
L(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ L_0(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[ P_L L_L^n(x) \cos\left(\frac{ny}{R}\right) + P_R L_R^n(x) \sin\left(\frac{ny}{R}\right) \right] \right\}, \\
E(x, y) &= \frac{1}{\sqrt{\pi R}} \left\{ e_R(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[ P_R e_R^n(x) \cos\left(\frac{ny}{R}\right) + P_L e_L^n(x) \sin\left(\frac{ny}{R}\right) \right] \right\}, \\
D_M L(x, y) &= \left( \partial_M + i g_2^1 W_M + i \frac{y_1^1}{2} g_1^5 B_M \right) L(x, y), \\
D_M E(x, y) &= \left( \partial_M + i \frac{y_2^1}{2} g_1^5 B_M \right) E(x, y), \\
D_M Q(x, y) &= \left( \partial_M + i g_3^5 G_M + i g_2^5 W_M + i \frac{y_4^1}{2} g_1^5 B_M \right) Q(x, y), \\
D_M U(x, y) &= \left( \partial_M + i g_3^5 G_M + i \frac{y_4^1}{2} g_1^5 B_M \right) U(x, y), \\
D_M D(x, y) &= \left( \partial_M + i g_3^5 G_M + i \frac{y_5^1}{2} g_1^5 B_M \right) D(x, y).
\end{align*}
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \cos\left(\frac{my}{R}\right) \cos\left(\frac{ny}{R}\right) = \frac{\pi R}{2} \delta_{m,n}, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \sin\left(\frac{my}{R}\right) \sin\left(\frac{ny}{R}\right) = \frac{\pi R}{2} \delta_{m,n}, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \cos\left(\frac{my}{R}\right) \cos\left(\frac{ny}{R}\right) \cos\left(\frac{ly}{R}\right) = \frac{\pi R}{4} \Delta^1_{mnl}, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \cos\left(\frac{my}{R}\right) \cos\left(\frac{ny}{R}\right) \cos\left(\frac{ky}{R}\right) \cos\left(\frac{ly}{R}\right) = \frac{\pi R}{8} \Delta^2_{mnlk}, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \sin\left(\frac{my}{R}\right) \sin\left(\frac{ny}{R}\right) \sin\left(\frac{ly}{R}\right) \sin\left(\frac{ky}{R}\right) = \frac{\pi R}{8} \Delta^3_{mnlk}, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \sin\left(\frac{my}{R}\right) \sin\left(\frac{ny}{R}\right) \cos\left(\frac{ly}{R}\right) \cos\left(\frac{ky}{R}\right) = \frac{\pi R}{8} \Delta^4_{mnlk}, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \sin\left(\frac{my}{R}\right) \cos\left(\frac{ny}{R}\right) \cos\left(\frac{ly}{R}\right) = 0, \]
\[ \frac{1}{2} \int_{-\pi R}^{\pi R} dy \sin\left(\frac{my}{R}\right) \cos\left(\frac{ny}{R}\right) \sin\left(\frac{ly}{R}\right) = 0, \]
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KK states after Compactification

- Each SM particle has an infinite number of KK partners, with mass
  \[ \sqrt{m^2 + \frac{n^2}{R^2}} \]
- KK particles have the same spin as SM particles.
- There are TWO Dirac KK fermions for each SM fermion.

- **Q**
  - L
  - R
  - \( n = 3 \)
  - \( n = 2 \)
  - \( n = 1 \)
  - \( n = 0 \)

- **U**
  - L
  - R
  - \( n = 3 \)
  - \( n = 2 \)
  - \( n = 1 \)
  - \( n = 0 \)

- **A**
  - \( A_\mu \)
  - \( A_5 \)
  - \( n = 3 \)
  - \( n = 2 \)
  - \( n = 1 \)
  - \( n = 0 \)
### KK states after Compactification

<table>
<thead>
<tr>
<th>SU(2) Symmetry</th>
<th>SM mode</th>
<th>KK mode</th>
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</thead>
<tbody>
<tr>
<td>Quark doublet</td>
<td>$q_L(x) = \begin{pmatrix} U_L(x) \ D_L(x) \end{pmatrix}$</td>
<td>$Q^n_L(x) = \begin{pmatrix} U^n_L(x) \ D^n_L(x) \end{pmatrix}$, $Q^n_R(x) = \begin{pmatrix} U^n_R(x) \ D^n_R(x) \end{pmatrix}$</td>
</tr>
<tr>
<td>Lepton doublet</td>
<td>$L_0(x) = \begin{pmatrix} \nu_L(x) \ E_L(x) \end{pmatrix}$</td>
<td>$L^n_L(x) = \begin{pmatrix} \nu^n_L(x) \ E^n_L(x) \end{pmatrix}$, $L^n_R(x) = \begin{pmatrix} \nu^n_R(x) \ E^n_R(x) \end{pmatrix}$</td>
</tr>
<tr>
<td>Quark Singlet</td>
<td>$u_R(x)$</td>
<td>$u^n_R(x), u^n_L(x)$</td>
</tr>
<tr>
<td>Quark Singlet</td>
<td>$d_R(x)$</td>
<td>$d^n_R(x), d^n_L(x)$</td>
</tr>
<tr>
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<td>$e_R(x)$</td>
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<table>
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<tr>
<th>KK Fermions</th>
<th>$I_3$</th>
<th>$Y$</th>
<th>$Q = I_3 + \frac{y}{2}$</th>
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<tbody>
<tr>
<td>Quark Doublet</td>
<td>$U_n = U^n_L(x) + U^n_R(x)$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
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<tr>
<td></td>
<td>$D_n = D^n_L(x) + D^n_R(x)$</td>
<td>$-\frac{1}{2}$</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>Quark Singlet</td>
<td>$u_n = u^n_L(x) + u^n_R(x)$</td>
<td>$0$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td></td>
<td>$d_n = d^n_L(x) + d^n_R(x)$</td>
<td>$0$</td>
<td>$-\frac{2}{3}$</td>
</tr>
<tr>
<td>Lepton Doublet</td>
<td>$\nu_n = \nu^n_L(x) + \nu^n_R(x)$</td>
<td>$\frac{1}{2}$</td>
<td>$-1$</td>
</tr>
<tr>
<td></td>
<td>$E_n = E^n_L(x) + E^n_R(x)$</td>
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<td>$-1$</td>
</tr>
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<td>Lepton Singlet</td>
<td>$e_n = e^n_L(x) + e^n_R(x)$</td>
<td>$0$</td>
<td>$-2$</td>
</tr>
<tr>
<td>no KK singlet $\nu^n$</td>
<td>-</td>
<td>-</td>
<td>-</td>
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KK states after Compactification

- All vertices at tree level satisfy KK number conservation.

\[
\begin{align*}
|m \pm n \pm k| &= 0, \\
|m \pm n \pm k \pm l| &= 0.
\end{align*}
\]

- KK parity, \((-1)^n\) is always conserved even at higher order.

- New vertices are basically the same as the SM couplings (up to normalization factor).
Overview on UED

• Universal: all SM particles in flat ED (no gravity)
• The simplest model: S1/Z2 (5D)
• KK tower after compactification with n/R
• KK-parity: \((-1)^n\)
  – all SM particles (zero mode) are even
  – level 1 KK particles \((n=1)\) are odd
  – level 2 KK particles \((n=2)\) are even
  – electroweak precision constraints are avoided
    • new contributions are loop-suppressed
  – the LKP is stable and a DM candidate

![Diagram of S1/Z2 compactification](image)

Appelquist, Cheng, Dobrescu 2001

Appelquist, Yee 2002
More on UED

- Minimal UED: mass splitting be generated by radiative corrections (assuming no boundary terms and no bulk masses)
- Short RG running leads to compressed mass spectrum
- Two parameters: $R$, Lambda (cutoff)

$1/R = 500 \text{ GeV}$

Cheng, Matchev, Schmaltz, 2002
More on UED

- Two parameters: R, Lambda (cutoff)
- The same spin: SM and KK partners
- Larger production cross sections (compared to SUSY productions), i.e., KK gluon, KK quark productions
- Decay products are softer
- 4 leptons with large branching fractions

![Diagram with particles and kinematics](image)
Current bounds from LHC

- Collider and low energy experiments provide lower bound on KK scale (1/R)
- Minimal UED (2 parameters) is very constrained
- Cutoff dependence is logarithmic

Belyaev, Brown, Moreno, Papineau 2012
The cross-section upper limits are set for the mUED model in the 2D parameter space $1/R$ (GeV) vs $\Lambda$ (TeV). The observed limit is given by $\sigma = 20.1 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$, integrating over the dimuon signal region. Model-independent limits are derived using the CL$_{S}$ prescription. Numbers give 95% CL upper limits on expected and observed model cross sections [pb].
SUSY is an ED theory

- SUSY is an extra dimension theory with anti commuting coordinate

\[ \Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha \theta_\alpha \]

<table>
<thead>
<tr>
<th>Field</th>
<th>SUSY</th>
<th>UED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetry</td>
<td>Supersymmetry</td>
<td>5D Lorentz and gauge symmetry (broken by compactification and boundary interactions)</td>
</tr>
<tr>
<td>Component fields</td>
<td>(SM, Superpartner)</td>
<td>(SM, KK partners)</td>
</tr>
<tr>
<td></td>
<td>( \Phi ) in terms of ( \theta ) and ( \theta^* )</td>
<td>( \Phi ) in terms of bases ( \exp(y), \cos(y), \sin(y) )</td>
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<tr>
<td>Spins</td>
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<td>same spins</td>
</tr>
<tr>
<td>( \mathcal{L}_{eff} )</td>
<td>( \int d\theta d\theta^* S[\Phi(x, \theta, \theta^*)] )</td>
<td>( \int dy S[\Phi(x, y)] )</td>
</tr>
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<td>KK-parity = ((-1)^n)</td>
</tr>
<tr>
<td># of parameters</td>
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<td>many (boundary terms)</td>
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<td>2 in MUED ( (R, \Lambda) )</td>
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**Table**: Comparison of SUSY and UED

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SUSY vs UED

- SUSY-like cascade decays at the LHC from the first KK modes.

- Distinct feature: 2nd KK modes.

\[ \text{SUSY: } \tilde{q} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad UED: \quad Q_1 \]

\[ Z_1 \quad \tilde{\chi}_2^0 \quad \ell^\pm \text{(near)} \quad \ell^\mp \text{(far)} \]

\[ \tilde{\chi}_1^0 \quad \gamma_1 \]

\[ V_2 \quad f_0 \quad f_0 \quad V_2 \quad f_1 \quad f_1 \quad V_1 \quad \bar{f}_0 \]

**Figure 3.** The effective $f_0 V_2^\mu f_0$ KK-number violating coupling on the left is generated at one loop order from the one loop diagram on the right.
Spin and Couplings of Dark Matter: Why is it difficult to measure them?

- Missing energy signatures arise from something like:

- Several alternative explanations:
Coupling vs. mass current limits: $G'$

$$g_s \tan \theta \bar{q} \gamma^\mu T^a G'^a_{\mu q}$$

$M_{G'}$ (GeV)

Wide resonance

Non-minimal models

UA2

CDF Run I

CDF 1.1 fb$^{-1}$

CMS 1 fb$^{-1}$

CMS 4 fb$^{-1}$

CMS 5 fb$^{-1}$

ATLAS 13 fb$^{-1}$

ATLAS 20 fb$^{-1}$

Dobrescu, Yu 2013

taken from Felix's talk
Coupling vs. mass projections: $G'$

14 and 33 TeV 95% C.L. exclusions, statistical uncertainties only

Yu 2013

taken from Felix’s talk
Current/projected bounds on level-2 KK gluon

Kong, Yu 2013

\[
SU(3)_c \text{ gauge boson} \quad \text{Quark (up)} \quad ig_3 \frac{\lambda^A}{2} \gamma^\mu \frac{1}{\sqrt{2}} \frac{1}{16\pi^2} \ln \left(\frac{\Lambda}{\mu}\right)^2 \left[ P_L \left( \frac{1}{8}g_1^2 + \frac{27}{8}g_2^2 - \frac{11}{2}g_3^2 \right) + P_R \left( 2g_1^2 - \frac{11}{2}g_3^2 \right) \right]
\]

\[
G_2 \quad \text{Quark (down)} \quad ig_3 \frac{\lambda^A}{2} \gamma^\mu \frac{1}{\sqrt{2}} \frac{1}{16\pi^2} \ln \left(\frac{\Lambda}{\mu}\right)^2 \left[ P_L \left( \frac{1}{8}g_1^2 + \frac{27}{8}g_2^2 - \frac{11}{2}g_3^2 \right) + P_R \left( \frac{1}{2}g_1^2 - \frac{11}{2}g_3^2 \right) \right]
\]
Level 2: KK (dilepton) resonances

In conclusion of this section, we discuss the experimental s...
Level 2: KK (dilepton) resonances

\[ \Delta m_{ee}/m_{ee} \approx 1\% \]

\[ \frac{\Delta m_{\mu\mu}}{m_{\mu\mu}} = 0.0215 + 0.0128 \left( \frac{m_{\mu\mu}}{1 \text{ TeV}} \right) \]

Datta, Kong, Matchev 2005
Data Fit with MUED vs SM

ATLAS Preliminary

$W, Z \rightarrow bb$
\[ \sqrt{s} = 7 \text{ TeV}, \text{ Ldt} = 4.7 \text{ fb}^{-1} \]

$H \rightarrow \tau\tau$
\[ \sqrt{s} = 7 \text{ TeV}, \text{ Ldt} = 4.6 \text{ fb}^{-1} \]

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$
\[ \sqrt{s} = 8 \text{ TeV}, \text{ Ldt} = 13 \text{ fb}^{-1} \]

$H \rightarrow \gamma\gamma$
\[ \sqrt{s} = 7 \text{ TeV}, \text{ Ldt} = 4.6 \text{ fb}^{-1} \]

$H \rightarrow ZZ^{(*)} \rightarrow 4l$
\[ \sqrt{s} = 8 \text{ TeV}, \text{ Ldt} = 13 \text{ fb}^{-1} \]

Combined
\[ \mu = 1.35 \pm 0.24 \]

CMS Preliminary

$\sqrt{s} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1} \]

$\sqrt{s} = 8 \text{ TeV}, L \leq 19.6 \text{ fb}^{-1} \]

$\mu = 0.90 \pm 0.14$

Best fit $\sigma/\sigma_{SM}$

Belyaev, Belanger, Brown, Kakuzaki, Pukhov, 2012
There is no hint on MUED from the Higgs data …
The fit of the SM if perfect :-((
But SM does not predict DM!
The fit of MUED is good as well
factor, this is partly compensate by an increase in the contribution of coannihilation channels with KK leptons su הק"ס only SM particles. This still leaves around 10% contribution from all re
scale. This is due to the important contribution of the coannihilation c
level 2 masses, means that the pole e
state, the prediction for the relic abundance is close to the one obt
on the mass of the level-2 particle, a small downward shift in the mass
significantly the e
SM particles in the final state. Coannihilation channels involving lepton
the process
including di
the sum over final state color configurations, as before.

where,

Figure 5: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into fermions.

Figure 5: Feynman diagrams for $B^{(1)}B^{(1)}$ annihilation into Higgs scalar bosons.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Graphical Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a0) $\gamma^{(1)}$ annihilation (tree; w/o FS level 2)</td>
<td><img src="image1.png" alt="Graph1" /></td>
</tr>
<tr>
<td>a1) $\gamma^{(1)}$ annihilation (1-loop; w/o FS level 2)</td>
<td><img src="image2.png" alt="Graph2" /></td>
</tr>
<tr>
<td>b0) Coannihilation (tree; w/o FS level 2)</td>
<td><img src="image3.png" alt="Graph3" /></td>
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<tr>
<td>b1) Coannihilation (1-loop; w/o FS level 2)</td>
<td><img src="image4.png" alt="Graph4" /></td>
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<tr>
<td>c0) Coannihilation (tree; w/ FS level 2)</td>
<td><img src="image5.png" alt="Graph5" /></td>
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<tr>
<td>c1) Coannihilation (1-loop; w/ FS level 2)</td>
<td><img src="image6.png" alt="Graph6" /></td>
</tr>
</tbody>
</table>

Belanger, Kakizaki, Pukhov, 2010
Kong, Matchev, 2005

**Figure 3** we present the resulting relic abundance of
and three flavors of
and the red curves (lower of each pair)

$\Omega h^2 = 0.16 \pm 0.04$
**KKDM in non-minimal model**

- The change in the cosmologically preferred value for $R^{-1}$ as a result of varying the different KK masses away from their nominal MUED values (along each line, $\Omega h^2 = 0.1$)

  ![Graph](image.png)

  (Kong, Matchev, hep-ph/0509119)

- In nonminimal UED, Cosmologically allowed LKP mass range can be larger
  - If $\Delta = \frac{m_1 - m_{\gamma_1}}{m_{\gamma_1}}$ is small, $m_{LKP}$ is large, UED escapes collider searches
    → But, good news for dark matter searches
KK Dark Matter: complementarity

- Treat the LKP mass and mass splitting as free parameters.
- Gives a better chance for the LHC, and direct detection.

Yellow: 4 leptons plus MET at 14 TeV LHC with 100 fb-1
Green: relic abundance

Arrenberg, Baudis, Kong, Matchev, Yoo 2013
How Many Extra Dimensions?

- Extra “spinless” states: GH, ZH, WH, BH
- KK photon is a not DM and decays to spinless photon via 1-loop 2 body or tree-level 3 body decay (with vanishing BC at cutoff scale)
Multi-leptons from 2UED

\[ \sigma(pp \rightarrow n\ell + m\gamma + \not{E}_T, n \geq n_{\text{min}}) = \sum_{i=1}^{11} \sum_{j \geq i}^{11} \sigma(pp \rightarrow A_i^{(1)} A_j^{(1)}) B_{ij} \]

\[ B_{ij} = \sum_{a,b=0}^{4} \sum_{a',b'=0}^{1} \text{Br}(i,a,a') \text{Br}(j,b,b') \]

\[ 0 \leq n + 2m \leq 8 \]

- The number of multi-lepton events at 14 TeV LHC
- No acceptance cuts
**Leptons and Photons from 2UED**

- The number of lepton + photon events (14 TeV)

---

**Figure 12:**
Cross sections for (a) $m \gamma + n \ell +/\ E_T$ events with $n \geq n_{\text{min}}$ for $m = 1, 2$ and $1 \leq n_{\text{min}} \leq 4$ and (b) Lepton + photon events with two or more same-sign leptons, at the LHC as a function of $1/R$.

**Figure 13:**
Representative processes that lead to $5 \ell +/\ E_T$ and $\gamma \ell + \ell^- +/\ E_T$ events. Several other production mechanisms as well as cascade decays contribute to these and related signals.
Spinless Photon Dark Matter

- \( R^{-1} < 600 \) GeV
- Light higgs requires light KK particles → large production cross-sections at the LHC/Tevatron
- Oblique corrections: \( R_{\text{inv}} > 900 \) GeV
- Relic abundance: \( R_{\text{inv}} < 600 \) GeV
- \( MH = 125-126 \) GeV

Dobrescu, Hooper, Kong, Mahbubani, 2007
Many Variations

- **MUED:** Minimal Universal Extra Dimensions (cf. mSugra)
- **2UED:** Two Universal Extra Dimensions (cf. GMSB)
- **nUED:** non-minimal Universal Extra Dimensions
  - boundary terms
- **SUED:** Split Universal Extra Dimensions (cf. Split SUSY)
  - bulk terms
- **sUED:** UED with singlet extension
- **NMUED:** Next-to-Minimal UED (cf. pMSSM)
  - (with boundary and bulk terms)
- Many others with larger gauge groups (cf. SU(2)L x SU(2)R)
Next-to-Minimal UED

\[ S_5 = \int d^4x \int_{-L}^L dy \left[ \mathcal{L}_V + \mathcal{L}_\Psi + \mathcal{L}_H + \mathcal{L}_{Yuk} \right] \]

\[ \mathcal{L}_V = \sum_A -\frac{1}{4} A^{MN} \cdot A_{MN} \]

\[ \mathcal{L}_\Psi = \sum_{\Psi=Q,U,D,L,E} i\Psi \bar{D}_M \Gamma^M \Psi - M_\Psi \bar{\Psi} \Psi \]

\[ \mu_\theta(y) = M_{Q,L} = -M_{U,D,E} \]

\[ M_\Psi(y) = -M_\Psi(-y). \]

\[ \mathcal{L}_H = (D_M H)^\dagger D^M H - V(H), \]

\[ V(H) = -\mu_5^2 |H|^2 + \lambda_5 |H|^4, \]

\[ \mathcal{L}_{Yuk} = \lambda_5^E \bar{L}HE + \lambda_5^D \bar{Q}HD + \lambda_5^U \bar{Q}\tilde{H}D + \text{h.c.} \]

\[ S_{bdy} = \int d^4x \int_{-L}^L dy \left( \mathcal{L}_\partial V + \mathcal{L}_\partial \Psi + \mathcal{L}_\partial H + \mathcal{L}_\partial Y_{uk} \right) [\delta(y - L) + \delta(y + L)] \]

\[ L = \pi R/2 \]
fermion bulk masses $M_{Q,U,D,L,E}$
boundary gauge parameters $r_G, r_W, r_B$
boundary Higgs parameters $r_H, r_\mu, r_\lambda$
boundary fermion parameters $r_{Q,U,D,L,E}$
boundary Yukawa couplings $r_{\lambda U,D,E}$

- To avoid tree-level FCNC, set all $M$ and $r$ flavor blind $\rightarrow 19$.
- For $r_\mu \neq r_\lambda$, bulk VEV and boundary VEV different.
- To avoid KK mode mixing, set all $r$'s the same.
- Assume universal bulk masses $\rightarrow$ two extra parameters in addition to $R$ and Lambda (cutoff)
Fermions

\[
\Psi(x, y) = \sum_{n=0}^{\infty} \left( \psi_L^{(n)}(x)f_n^\Psi_L(y) + \psi_R^{(n)}(x)f_n^\Psi_R(y) \right)
\]

\[
k_n \cos(k_n L) = (r (m_{f_n})^2 + \mu) \sin(k_n L) \quad \text{for odd } n,
\]

\[
rk_n \cos(k_n L) = -(1 + r \mu) \sin(k_n L) \quad \text{for even } n,
\]

\[
m_{f_n} = \sqrt{k_n^2 + \mu^2},
\]

\[
\mathcal{N}_n^\Psi = \begin{cases} 
\sqrt{\frac{\mu}{(1+2r \mu) \exp(2\mu L) - 1}} & \text{for } n = 0, \\
\sqrt{\frac{1}{\cos(k_n L) \sin(k_n L) - 2r \sin^2(k_n L)}} & \text{for odd } n, \\
\sqrt{\frac{1}{\cos(k_n L) \sin(k_n L)}} & \text{for even } n,
\end{cases}
\]

\[
\int_{-L}^{L} dy f_m^\Psi_L f_n^\Psi_L [1 + r (\delta(y + L) + \delta(y - L)] = \delta_{mn},
\]

\[
\int_{-L}^{L} dy f_m^\Psi_R f_n^\Psi_R = \delta_{mn}.
\]
\[ A_{\mu}(x, y) = \sum_{n=0}^{\infty} A^{(n)}_{\mu}(x) f^{A}_n(y), \]
\[ H(x, y) = \sum_{n=0}^{\infty} H^{(n)}(x) f^{A}_n(y). \]
\[ \cot(k_n L) = r k_n \quad \text{for odd } n, \]
\[ \tan(k_n L) = -r k_n \quad \text{for even } n, \]
\[ m_{\gamma_n} = k_n. \]

For \( n = 0 \):
\[ f^{A}_0(y) = \frac{1}{\sqrt{2L(1 + r/L)}}. \]
\[ \text{odd } n : \quad f^{A}_n(y) = \sqrt{\frac{1}{L + r \sin^2(k_n L)}} \sin(k_n y), \]
\[ \text{even } n : \quad f^{A}_n(y) = \sqrt{\frac{1}{L + r \cos^2(k_n L)}} \cos(k_n y), \]

\[ \int_{-L}^{L} dy f^{A}_m f^{A}_n [1 + r (\delta(y + L) + \delta(y - L))] = \delta_{mn}. \]
NMUED: tree-level spectrum

- "r" decreases masses of KK bosons and KK fermions
- "mu" increases masses of KK fermions (demand: $\mu < 0$)
- No loop corrections --> no dependence on cutoff

$L = \pi R / 2$

Flacke, Kong, Park 2013
Couplings

\[ S_{\text{eff}} \supset \int d^4x \sqrt{g} \psi^{(0)}_{L/R} \bar{A}^{(0)} \psi^{(0)}_{L/R} \int_{-L}^{L} dy f_0^A f_0^\Psi f_0^\Psi \left[ 1 + r (\delta(y + L) + \delta(y - L)) \right] \]

\[ = \int d^4x \sqrt{2L(1 + r/L)} \psi^{(0)}_{L/R} \bar{A}^{(0)} \psi^{(0)}_{L/R}, \]

\[ g_{110}^A = g_A^5 \int dy \left[ 1 + r (\delta(y + L) + \delta(y - L)) \right] f_1^A f_1^\Psi f_0^\Psi \equiv g_A^A F_{110} \]

\[ g_{220}^A = g_A^5 \int dy \left[ 1 + r (\delta(y + L) + \delta(y - L)) \right] f_2^A f_2^\Psi f_0^\Psi \equiv g_A^A F_{220} \]

\[ g_{211}^A = g_A^5 \int dy \left[ 1 + r (\delta(y + L) + \delta(y - L)) \right] f_2^A f_1^\Psi f_1^\Psi \equiv g_A^A F_{211} \]

\[ g_{200}^A = g_A^5 \int dy \left[ 1 + r (\delta(y + L) + \delta(y - L)) \right] f_2^A f_0^\Psi f_0^\Psi \equiv g_A^A F_{200} \]

\[ g_A^5 = g_A \sqrt{2L \left( 1 + \frac{r}{L} \right)} \]

\[ \mu_5 = \mu_H \]

\[ \lambda_5 = \lambda_H \left( 2L \left( 1 + \frac{r}{L} \right) \right) \]

\[ \lambda_5^{U,D,E} = \lambda^{U,D,E} \sqrt{2L \left( 1 + \frac{r}{L} \right)} \]

Kong, Park, Rizzo 2010
NMUED: couplings (\(\mu<0\))

Figure 2. Modified KK couplings: \(V_1 f_1 f_0\) (top-left), \(V_2 f_2 f_0\) (top-right), \(V_2 f_1 f_1\) (bottom-left), and \(V_2 f_0 f_0\) (bottom-right). Couplings are only induced at one-loop level and therefore small, but still potentially observable at LHC when upgraded to 14 TeV. As can be seen in the right panel of Fig. 2, for our generalized UED setup, the coupling is absent only for \(\mu=0\) – again due to coinciding fermion and gauge boson wave functions and the orthogonality relations. For generic \(\mu\), \(g_A^{200}\) is of the order of the corresponding standard model coupling. Therefore, resonance searches are amongst the most sensitive tests of generalized UED models. We find that dependence on the brane parameter \(r\) is weak in \(F_{110}\) and \(F_{200}\) and we expect that they may be less constrained by experiments. On the other hand, variation of \(F_{220}\) and \(F_{211}\) along the \(r\) direction is more dramatic.

3 Constraints on Generalized UED Models
In this section, we consider various constraints on the generalized UED model in the presence of bulk masses and brane localized terms.
CMS PAPER EXO-11-024

$\mathcal{L} = 4.7 \text{ fb}^{-1}$

Models and interpretations

- $W - W'$ interferences considered (left-handed $W'$)
- UED: $W'_{KK}(n = 2, 4, ..)$ (coupling to SM fermions)

Lepton channels $\ell = e, \mu$ (+ $E_T^{\text{miss}}$)

- $W$ boson transverse mass reconstruction
  \[ M_T = \sqrt{2 \cdot \ell_T \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta \phi_{\ell, \nu})} \]

Bayesian exclusion limits at 95% C.L.

- Higher order EW corrections (not plotted) at high masses reduce interference effects
- Limit on $m_{W'}$ (right-handed): 2.5 TeV, on $m_{W'}$ (left-handed): 2.63 TeV [2.43 TeV] for constructive [destructive] $W - W'$ interference
- Universal Extra Dimension re-interpretation:
  Limits in terms of ED Radius $R$ and Dirac mass term $\mu$
  No sensitivity to $n \geq 4$ modes (yet)
Figure 1: Oblique (S, T, U) bonds on R₁ with the latest Gfitter data with mₕ = 126 GeV. The plots show contours of minimally allowed R₁ in the rₜ/L vs. µₜ/L parameter space for r₉L = 0 (left) and r₉L = 1 (right). The shaded areas are excluded because there, the lightest Kaluza-Klein particle is a KK bottom, thereby representing a charged dark matter particle.

We present all results as bounds on the compactification scale R₁ as a function of the dimensionless parameters µₜ/L and rₜ/L. To indicate the effect of a common boundary term, we show constraints for r₉L = 0 ("vanishing boundary parameter") and r₉L = 1 ("typical boundary parameter").

The electroweak bounds shown in Fig. 1 are obtained by performing a 2 fit of the parameters SUED, TUED, UUED from Eq. (5.3) to the experimental values given in Ref. [45]:

S NP = 0.03 ± 0.10, T NP = 0.05 ± 0.12, U NP = 0.03 ± 0.10,

(6.1)

for a reference point mₕ = 126 GeV and mₜ = 173 GeV with correlation coefficients of +0.89 between S NP and T NP, and 0.54 (0.83) between S NP and U NP (T NP and U NP).

An NDA estimate for the boundary parameter yields r/L ≈ R, where R gives an estimate for the number of KK levels below the cut-off scale.

Figure 2: Constraints from higgs searches at ATLAS and CMS combined. The plots show contours of minimally allowed R₁ in the rₜ/L vs. µₜ/L parameter space for r₉L = 0 (left) and r₉L = 1 (right). The shaded areas are excluded because there, the lightest Kaluza-Klein particle is a KK bottom, thereby representing a charged dark matter particle.

7 Summary and outlook

Acknowledgments

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AMS-02 and NMUED

- positron data disfavors universal boundary term and universal bulk mass
- Dijet constraints and indirect detection indicates more complicated structure \( \mu_{u,d} < \mu_{c,s} < \mu_{t,b} \) \( \mu_{t_L} \neq \mu_{t_R} \) and \( \mu_{q_L} \neq \mu_{q_R} \)
Exotic TTbar resonance

FIG. 3. (a) Production cross section of $gg \rightarrow G_3 t \bar{t}$ and $pp \rightarrow G_3 t \bar{t}$. (b) Production cross section of $gg \rightarrow G_3 t \bar{t}$ in $M_{G_3 t \bar{t}}$ space.

C. BRs

For four top final state:

$$BR(t \rightarrow bW \rightarrow b \nu_\tau \bar{\nu}_\tau) = 0.22,$$

$$BR(t \rightarrow bW \rightarrow b \nu_\tau jj) = 0.67$$

without $\nu$.

$$BR(t \bar{t} \rightarrow t \bar{t} \rightarrow 4 \text{ leptons} + X) = 0.22,$$

$$BR(t \bar{t} \rightarrow t \bar{t} \rightarrow 4 \text{ leptons} + X) = 0.00234,$$

$$BR(t \bar{t} \rightarrow t \bar{t} \rightarrow \text{at least 3 leptons} + X) = 6 \times 0.22 = 0.2904,$$

$$BR(t \bar{t} \rightarrow t \bar{t} \rightarrow \text{at least 2 leptons} + X) = 6 \times 0.22 = 0.2904.$$


Summary

• MH=126 GeV and relic abundance disfavors 2UED with minimal mass spectrum

• MUED is very constrained
  – Rinv > 1.2-1.3 TeV from tri-lepton search (8 TeV)
  – Rinv < 1.5 TeV from relic abundance

• NMUED introduces brane terms and bulk masses
  – More parameter space, and hence tension reduced
  – Can accommodate Higgs in broad parameter space
  – Positron/antiproton data disfavors universal parametrization
  – dijet+positron data indicates more complicated structure
  – MUED exists in various event generators: CalcHEP, PYTHIA, MG/ME, Herwig, Sherpa, etc
  – For NMUED, coupling and mass spectrum can be modified
Why Consider Exotica?

• Some exotica aren’t really all that exotic
• Urgent – real possibilities for 2015-????
• You have the potential to advance science

  
  Would experimentalists have thought of this if you didn’t do this work?
  – Witten

• …and you might actually advance science

  
  Never start a project unless you have an unfair advantage.
  – Seiberg
• It’s fun

If every individual student follows the same current fashion ..., then the variety of hypotheses being generated...is limited. Perhaps rightly so, for possibly the chance is high that the truth lies in the fashionable direction. But, on the off-chance that it is in another direction - a direction obvious from an unfashionable view ... -- who will find it? Only someone who has sacrificed himself...I say sacrificed himself because he most likely will get nothing from it...But, if my own experience is any guide, the sacrifice is really not great because...you always have the psychological excitement of feeling that possibly nobody has yet thought of the crazy possibility you are looking at right now.

– Richard Feynman, Nobel Lecture
Back up
• SUSY-like cascade decays at the LHC from the first KK modes.

• Distinct feature: 2nd KK modes...
Spin and Couplings of Dark Matter: Why is it difficult to measure them?

- Missing energy signatures arise from something like:

- Several alternative explanations:

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Burns, Kong, Matchev, Park 2008
What is a good distribution to look at?

- Invariant mass distributions!
- Advantages: well studied, know about spin. For adjacent SM particles
  \[ \frac{dN}{dm^2} = a_0 + a_2 m^2 + a_4 m^4 + \ldots \]
  - Plot versus \( m^2 \)!
  - For an intermediate BSM particle of spin \( s \), the highest order term is \( m^{4s} \)
  - For non-adjacent BSM particles, there are log terms as well.
- Disadvantage: know about many other things (hidden in the coefficients \( a \)), not all of which are measured!
  - Masses \( M_A, M_B, M_C, M_D \) (x,y,z)
  - Couplings and mixing angles (\( g_L \) and \( g_R \))
  - Particle-antiparticle (D/D*) fraction \( (f/f^*) \) (\( f + f^* = 1 \))
What is the relevant question?

• Given the data, which spin configuration gives a good fit for arbitrary values of the yet unknown parameters?
  – fix mass spectrum
  – let spins, couplings, mixing angles, particle/antiparticle fraction $f$, etc. to float

• Previously people had asked: Given the data, which spin configuration gives a good fit for fixed values (the true ones) of the yet unknown parameters?
  – They fix: everything but the spins
  – Then let spins to float

• What is wrong with the latter approach?
  – It’s the wrong chronological order
  – To measure the chirality of the couplings, we will probably need to measure the spins first
  – It’s not a pure spin measurement, i.e. it is a spin measurement under certain model assumptions which still need to be verified experimentally
How do we do it?

• Separate the spin dependence from all the rest
  – Parameterize conveniently the effect from “all the rest”

\[
\left( \frac{dN}{dm^2} \right)_S = F_{S;\delta}(m^2) + \alpha F_{S;\alpha}(m^2) + \beta F_{S;\beta}(m^2) + \gamma F_{S;\gamma}(m^2)
\]

• Measure both the spin (S) as well as all the rest: \( \alpha, \beta, \gamma \)

\[
\alpha(\varphi_b, \varphi_a) = \cos 2\varphi_b \cos 2\varphi_a, \\
\beta(\varphi_c, \varphi_b) = \cos 2\varphi_c \cos 2\varphi_b = (f - \bar{f}) \cos 2\varphi_c \cos 2\varphi_b \\
\gamma(\varphi_a, \varphi_c) = \cos 2\varphi_a \cos 2\varphi_c = (f - \bar{f}) \cos 2\varphi_a \cos 2\varphi_c
\]

\[
\tan \varphi_a = \left| \frac{a_R}{a_L} \right|, \quad \tan \varphi_b = \left| \frac{b_R}{b_L} \right|, \quad \tan \varphi_c = \left| \frac{c_R}{c_L} \right|
\]
What is the method?

- Construct and then fit the three invariant mass distributions to

\[
L_{S}^{+-}(\hat{m}^{2}_{\ell\ell}; x, y, z, \alpha) \equiv \left( \frac{dN}{d\hat{m}^{2}_{\ell\ell}} \right)_{S} = \mathcal{F}^{(\ell\ell)}_{S;\delta}(\hat{m}^{2}_{\ell\ell}; x, y, z) + \alpha \mathcal{F}^{(\ell\ell)}_{S;\alpha}(\hat{m}^{2}_{\ell\ell}; x, y, z) ,
\]

\[
S_{S}^{+-}(\hat{m}^{2}_{j\ell}; x, y, z, \alpha) \equiv \left( \frac{dN}{d\hat{m}^{2}_{j\ell}} \right)_{S} + \left( \frac{dN}{d\hat{m}^{2}_{j\ell}} \right)_{S}
= r^{2} n \mathcal{F}^{(j\ell n)}_{S;\delta}(r^{2} \hat{m}^{2}_{j\ell}; x, y, z) + r^{2} f \mathcal{F}^{(j\ell f)}_{S;\delta}(r^{2} \hat{m}^{2}_{j\ell}; x, y, z) + \alpha r^{2} f \mathcal{F}^{(j\ell f)}_{S;\alpha}(r^{2} \hat{m}^{2}_{j\ell}; x, y, z) ,
\]

\[
D_{S}^{+-}(\hat{m}^{2}_{j\ell}; x, y, z, \beta \gamma) \equiv \left( \frac{dN}{d\hat{m}^{2}_{j\ell}} \right)_{S} - \left( \frac{dN}{d\hat{m}^{2}_{j\ell}} \right)_{S}
= \gamma r^{2} f \mathcal{F}^{(j\ell f)}_{S;\gamma}(r^{2} \hat{m}^{2}_{j\ell}; x, y, z) + \beta^{2} f \mathcal{F}^{(j\ell f)}_{S;\beta}(r^{2} \hat{m}^{2}_{j\ell}; x, y, z) - \beta r^{2} n \mathcal{F}^{(j\ell n)}_{S;\beta}(r^{2} \hat{m}^{2}_{j\ell}; x, y, z)
\]

\[
\alpha(\varphi_{b}, \varphi_{a}) = \cos 2\varphi_{b} \cos 2\varphi_{a} ,
\]

\[
\beta(\tilde{\varphi}_{c}, \varphi_{b}) = \cos 2\tilde{\varphi}_{c} \cos 2\varphi_{b} = (f - \bar{f}) \cos 2\varphi_{c} \cos 2\varphi_{b}
\]

\[
\gamma(\varphi_{a}, \tilde{\varphi}_{c}) = \cos 2\varphi_{a} \cos 2\tilde{\varphi}_{c} = (f - \bar{f}) \cos 2\varphi_{a} \cos 2\varphi_{c}
\]
Coupling measurements

- The fitted values of alpha, beta, gamma represent measurements of certain combinations of couplings and mixing angles.
- The sign ambiguity corresponds to the chirality exchange.

\[
\begin{align*}
|a_L| &= \frac{1}{\sqrt{2}} \left( 1 \pm \frac{1}{\beta} \sqrt{\alpha \beta \gamma} \right)^{\frac{1}{2}}, \\
|a_R| &= \frac{1}{\sqrt{2}} \left( 1 \mp \frac{1}{\beta} \sqrt{\alpha \beta \gamma} \right)^{\frac{1}{2}}, \\
|b_L| &= \frac{1}{\sqrt{2}} \left( 1 \pm \frac{1}{\gamma} \sqrt{\alpha \beta \gamma} \right)^{\frac{1}{2}}, \\
|b_R| &= \frac{1}{\sqrt{2}} \left( 1 \mp \frac{1}{\gamma} \sqrt{\alpha \beta \gamma} \right)^{\frac{1}{2}}, \\
|c_L| &= \frac{1}{\sqrt{2}} \left( 1 \pm \frac{1}{f - f} \frac{1}{\alpha} \sqrt{\alpha \beta \gamma} \right)^{\frac{1}{2}}, \\
|c_R| &= \frac{1}{\sqrt{2}} \left( 1 \mp \frac{1}{f - f} \frac{1}{\alpha} \sqrt{\alpha \beta \gamma} \right)^{\frac{1}{2}},
\end{align*}
\]
Does this really make any difference?

• Yes! Dilepton invariant mass distribution. Data from SPS1a.

  Athanasiou, Lester, Smillie, Webber 06
  Burns, Kong, Matchev, Park 08

• Spins vary
• Everything else fixed to SPS1a values
• Easy to distinguish!

• Mass spectrum fixed to SPS1a values
• Everything else varies
• Difficult to distinguish!
Does this really make any difference?

- Yes! Lepton charge (Barr) asymmetry. Data: “UED” with SPS1a mass spectrum.

- Spins vary
- Everything else fixed to SPS1a values
- Easy to distinguish!

- Mass spectrum fixed to SPS1a values
- Everything else varies
- Difficult to distinguish!

Athanasiou, Lester, Smillie, Webber 06
Burns, Kong, Matchev, Park 08
With Infinite Statistics

Burns, Kong, Matchev, Park 08

• Separate the spin dependence from all the rest
  – Parameterize conveniently the effect from “all the rest”

\[
\left( \frac{dN}{dm^2} \right)_S = F_{S;\delta}(m^2) + \alpha F_{S;\alpha}(m^2) + \beta F_{S;\beta}(m^2) + \gamma F_{S;\gamma}(m^2)
\]

• Measure both the spin (S) as well as all the rest: \( \alpha, \beta, \gamma \)