Phenomenology of Universal Extra Dimensions

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Outline

• Universal Extra Dimensions (UEDs)

• Astrophysical Implications
  – Relic Density of KK Dark Matter
  – Direct Detection Limit

• Collider Phenomenology of UEDs
  – Level 2 search at the LHC
  – Spin determinations (at the LHC and a linear collider)

• Summary
Hints for New Physics Beyond the Standard Model

- **Dark Matter**: 23% of the unknown in the universe
  - Best evidence for new physics beyond the Standard Model: if the dark matter is the thermal relic of a WIMP, its mass should be of the weak scale
    \[ \Omega_{WIMP} \sim \left( \frac{1}{10^2 \alpha} \right)^2 \left( \frac{M_{WIMP}}{1 \text{ TeV}} \right)^2 \]
  - Requires a stable (electrically) neutral weakly interacting particle at \( \mathcal{O}(1) \) TeV
  - To be stable, it should be the lightest particle charged under a new symmetry

- **Electroweak precision measurements**
  - There is no evidence of deviations of the EW observables from the SM predictions
  - New physics contributions to the EW observables should be suppressed
  - Possible if new particles are charged under a new symmetry under which SM is neutral
  - Their contributions will be loop-suppressed and the lightest particle is stable

⇒ **Collider implications**:
  - Pair production of new particles
  - Cascade decays down to the lightest particle give rise to missing energy plus jets/leptons
  - KK-parity in UED
“Confusion scenario”

- What is new physics if we see jets/leptons + missing energy at the colliders?

- The standard answer: Supersymmetry with R-parity → for a long time, this was the only candidate

- From the above discussion, we see that any new physics satisfying hints we have may show up at the LHC with similar signals

- Michael Peskin’s name for different kinds of new heavy particles whose decay chains result in the same final state

- How can we discriminate SUSY from confusion scenarios?

- How do we know new physics is SUSY?

- UEDs, Little Higgs ···
Universal Extra Dimensions

- Each SM particle has an infinite number of KK partners
  - The number of KK states = $\Lambda R$ ($\Lambda$ is a cut-off)
- KK particle has the same spin as SM particle with a mass, $\sqrt{\frac{n^2}{R^2} + m^2}$
  - SM particles became massive through electroweak symmetry breaking
  - KK gauge bosons get masses by eating 5th components of gauge fields (Nambu-Goldstone bosons) and EWSB shifts those masses
- All vertices at tree level satisfy KK number conservation
  $$|m \pm n \pm k| = 0 \text{ or } |m \pm n \pm k \pm l| = 0$$
- KK number conservation is broken down to KK-parity, $(-1)^n$, at the loop level
  - The lightest KK partner at level 1 (LKP) is stable $\Rightarrow$ DM?
  - KK particles at level 1 are pair-produced
  - KK particles at level 2 can be singly produced
  - Additional allowed decays: $2 \rightarrow 00$, $3 \rightarrow 10$, $\cdots$
  - No tree-level contributions to precision EW observables
- New vertices are the same as SM interactions
  - Couplings between SM and KK particles are the same as SM couplings
  - Couplings among KK particles have different normalization factors
- There are two Dirac (KK) partners at each level $n$ for one Dirac fermion in SM
- For two UEDs, see Burdman’s talk
Tree level and radiative corrections


- Tree level mass $m_n = \sqrt{\left(\frac{n}{M}\right)^2 + m^2}$, $e_1$ is stable ···
- Radiative corrections are important!
- All but LKP decay promptly $\rightarrow$ missing energy signals
Relic Density Code

- **Kong and Matchev (UF, 2005)**
  - Fortran
  - Includes *all* level 1 KK particles
  - has a general KK mass spectra (all KK masses are, in principle, different)
  - can deal with different types of KK dark matter ($\gamma_1, Z_1, \nu_1 \cdots$)
  - improved numerical precision
    * use correct relativistic velocity expansion ($\langle \sigma v \rangle = a + b \langle v^2 \rangle$)
    * use temperature dependent degrees of freedom ($g_* = g_*(T_F)$)

- **Servant and Tait (Annecy/ANL, 2002)**
  - First code ($\gamma_1$ or $\nu_1$ dark matter)
  - has cross sections in Mathematica, assuming same KK masses
  - use approximate relativistic velocity expansion
  - use approximate degrees of freedom ($g_* = 92.25$)

- **Kribs and Burnell (Oregon/Princeton, 2005)**
  - has cross sections in Maple, assuming same KK masses ($\gamma_1$ dark matter)
  - do not use relativistic velocity expansion
  - deal with coannihilations with all level 1 KK

- **Kakizaki, Matsumoto and Senami (Bonn/KEK/Tokyo, 2006)**
  - interested in resonance effects ($\gamma_1$ dark matter) → See Senami’s talk
Improved result

(Kong, Matchev, hep-ph/0509119)

- Improvements in our calculation:
  - Include all coannihilations: many processes ($51 \times 51$ initial states)
  - Keep KK masses different in the cross sections:
  - Use temperature dependent $g_*$
  - Use relativistic correction in the b-term

- a: $\gamma_1\gamma_1$ annihilation only
  (from hep-ph/0206071)
- b: repeats the same analysis but
  uses temperature dependent $g_*$ and relativistic correction
- c: relaxes the assumption of KK mass degeneracy
- MUED: full calculation in MUED including all coannihilations with the proper choice of masses
- Preferred mass range: $500 - 600$ GeV
  for $0.094 < \Omega_{CDM} h^2 < 0.129$
  →See Senami’s talk for resonances
Dark matter in nonminimal UED

- 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 showing the cosmologically allowed LKP mass range in nonminimal UED](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
CDMS (Spin independent): $B_1$ and $Z_1$ LKP

(Baudis, Kong, Matchev, Preliminary)

- **SuperCDMS (projected)**
  - A (25 kg), B (150 kg), C (1 ton)

- $\Delta q_1 = \frac{m q_1 - m \gamma_1}{m \gamma_1}$

- **$Z_1$ LKP in nonminimal UED:**
  - $\Delta Q_1 = \frac{m Q_1 - m Z_1}{m Z_1}$
  - $\Delta g_1 = 0.2$
  - $\Delta_1 = 0.1$
Both have similar diagrams → same signatures!
  - At first sight, it is not clear which model we are considering

The decay chain is complicated

A lot of jets → correct jet identification is difficult → ISR/FSR add more confusion

UED discovery reach at the Tevatron and LHC: (Cheng, Matchev, Schmaltz, hep-ph/0205314)
  - Reach at the LHC: $R^{-1} \sim 1.5$ TeV with 100 fb$^{-1}$ in $4l + \not{E}_T$ channel
  - UED search by CMS group (full detector simulation)
  - See Dannheim’s talk for ATLAS study
How to discriminate:

- **Level 1 just looks like MSSM with LSP dark matter:**
  
  (Cheng, Matchev, Schmaltz, hep-ph/0205314)

- **Can we discriminate SUSY from UED?**

<table>
<thead>
<tr>
<th></th>
<th>SUSY</th>
<th>UED</th>
</tr>
</thead>
<tbody>
<tr>
<td>How many new particles</td>
<td>1*</td>
<td>KK tower</td>
</tr>
<tr>
<td>Spin of new particles</td>
<td>differ by $\frac{1}{2}$</td>
<td>same spins</td>
</tr>
<tr>
<td>Couplings of new particles</td>
<td>same as SM</td>
<td>same** as SM</td>
</tr>
<tr>
<td>Masses</td>
<td>SUSY breaking</td>
<td>boundary terms</td>
</tr>
<tr>
<td>Discrete symmetry</td>
<td>R-parity</td>
<td>KK-parity $= (-1)^n$</td>
</tr>
<tr>
<td>Dark matter</td>
<td>LSP ($\tilde{\chi}_1^0$)</td>
<td>LKP ($\gamma_1$)</td>
</tr>
<tr>
<td>Generic signature**</td>
<td>$E_T^*$</td>
<td>$E_T^*$</td>
</tr>
</tbody>
</table>

* $N = 1$ SUSY
** Couplings among some KK particles may have factors of $\sqrt{2}$, $\sqrt{3}$, $\cdots$
*** with dark matter candidates

- **Finding KK tower:** Datta, Kong, Matchev, hep-ph/0509246
- **Spin measurements:** Barr, hep-ph/0405052
  Smillie, Webber hep-ph/0507170
  Datta, Kong, Matchev, hep-ph/0509246 — see Plehn and Wang’s talks
- **Cross section:** Datta, Kane, Toharia, hep-ph/0510204
Implementation of UED in Event Generators

- **Datta, Kong and Matchev (UF, 2004)**
  - Full implementation of level 1 and level 2 in CompHEP/CalcHEP (spin information)
  - Provided for implementation in PYTHIA
  - Two different mass spectrum possible:
    * A general mass spectrum in Nonminimal UED
    * All masses/widths calculated automatically in Minimal UED
  - Used for dark matter study/collider studies
  - Used for ATLAS and CMS ($4\ell + \not{E}_T, nj + ml + \not{E}_T \cdots$)

- **Alexandre Alves, Oscar Eboli, Tilman Plehn (2006)** → see Plehn’s talk
  - Level 1 QCD and decays only in MADGRAPH (spin information!)

- **Wang and Yavin (Harvard, 2006)** → see Wang’s talk
  - Level 1 QCD and decays only in HERWIG (full spin information)

- **Smillie and Webber (Cambridge, 2005)**
  - Level 1 QCD and decays only in HERWIG (full spin information)

- **Peskin (Stanford, in progress)**
  - Level 1 QCD and decays only in PANDORA (full spin information)

- **El Kacimi, Goujdami and Przysiezniak (2005)**
  - Level 1 QCD and decays only in PYTHIA (spin information is lost)
  - Matrix elements from CompHEP/CalcHEP
Two resonances
(Datta, Kong, Matchev, hep-ph/0509246)

- Level 2 resonances can be seen at the LHC:
  - up to $R^{-1} \sim 1$ TeV for 100 fb$^{-1}$, $M_{ab}^2 = (p_a + p_b)^2$
  - covers dark matter region of MUED
- Mass resolution:
  - $\delta m = 0.01 M_{V_2}$ for $e^+e^-$
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1 \text{TeV}}\right)$ for $\mu^+\mu^-$
- Narrow peaks are smeared due to the mass resolution
- Two resonances can be better resolved in $e^+e^-$ channel
- Is this a proof of UED?
  - Not quite: resonances could still be interpreted as $Z$’s
  - Smoking guns:
    * Their close degeneracy
    * $M_{V_2} \approx 2 M_{V_1}$
    * Mass measurement of $W_2^\pm$ KK mode
- However in nonminimal UED models,
  degenerate spectrum is not required
  → just like SUSY with a bunch of $Z$’s
  → need spins to discriminate
Spin measurement

- Spin measurement is difficult
  - LSP/LKP is neutral → missing energy
  - There are two LSPs/LKPs ⇒ cannot find CM frame
  - Decay chains are complicated → cannot uniquely identify subchains
  - Look for something easy: look for 2 SFOS leptons, $\tilde{\chi}_2^0 \to \ell^\pm \ell^\mp \tilde{\chi}_1^0$ or $Z_1 \to \ell\ell_L^1 \to \ell^+\ell^-\gamma_1$
  - Dominant source of $\tilde{\chi}_2^0/Z_1$: squark/KK-quark decay

$$\tilde{q} \to q\tilde{\chi}_2^0 \to q\ell^\pm\ell^\mp \tilde{\chi}_1^0 \text{ or } Q_1 \to qZ_1 \to \ell\ell_L^1 \to \ell^+\ell^-\gamma_1:$$

- Study this chain: Observable objects are $q$ and $\ell^\pm$
- Can do: $M_{\ell^+\ell^-}$, $M_{q\ell^-}$ and $M_{q\ell^+}$ where $M_{ab}^2 = (p_a - p_b)^2$
- Which jet? Which lepton? Charge of jets ($q$ and $\tilde{q}$)?

$$M_{\ell^+\ell^-}, \text{ Asymmetry } = A^{+-} = \frac{(d\sigma/dm)_{q\ell^+} - (d\sigma/dm)_{q\ell^-}}{(d\sigma/dm)_{q\ell^+} + (d\sigma/dm)_{q\ell^-}} \text{ (Barr, Phys. Lett. B596:205-212, 2004)}$$

- Masses don’t discriminate
Dilepton distribution

- Look for spin correlations in $M_{\ell^+\ell^-}$
- Choose a study point in one model and fake mass spectrum in the other model

(Kong, Matchev Preliminary and Smillie, Webber hep-ph/0507170)

- Why are they the same?
Dilepton distribution

- How do we fake the \( M_{\ell^+\ell^-} \) distribution?

(Smillie, Webber hep-ph/0507170)

Phase Space: \[ \frac{dN}{dm} = 2\hat{m} \]

SUSY: \[ \frac{dN}{dm} = 2\hat{m} \]

UED: \[ \frac{dN}{dm} = \frac{4(y+4z)}{(1+2z)(2+y)} (\hat{m} + r \hat{m}^3) \]
[\( r = \frac{(2-y)(1-2z)}{y+4z} \)]

where \( \hat{m} = \frac{m_{\ell\ell}}{m_{\text{max}}^{\ell\ell}}, y = \left( \frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_0^0}} \right)^2 \) and \( z = \left( \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}} \right)^2 \)

- \( |r| \leq 0.4 \) in mSUGRA
Asymmetry

- Asymmetry with UED500 mass spectrum
  \((\mathcal{L} = 10\text{fb}^{-1})\)
  (Datta, Kong, Matchev, hep-ph/0509246)

- Asymmetry with SPS1a mass spectrum
  \((\mathcal{L} = 10\text{fb}^{-1})\)
  (Kong, Matchev Preliminary)

\[
\begin{align*}
Z_1 & \rightarrow \ell \ell^1 \rightarrow \ell^+ \ell^- \gamma_1 \\
\tilde{\chi}_2^0 & \rightarrow \ell \ell \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0
\end{align*}
\]

Chirality
\[
\begin{align*}
Z_1 & \rightarrow \ell \ell^1_R \rightarrow \ell^+ \ell^- \gamma_1 \\
\tilde{\chi}_2^0 & \rightarrow \ell \ell \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0
\end{align*}
\]
SPS1a mSUGRA point

(Kong, Matchev Preliminary)

- How to fake SPS1a asymmetry
  - five parameters in asymmetry: $f_q, x, y, z, m_{\tilde{q}}$
  - three kinematic endpoints: $m_{qll}, m_{ql}$ and $m_{ll}$
    * $m_{qll} = m_{\tilde{q}} \sqrt{(1-x)(1-yz)}$
    * $m_{ql} = m_{\tilde{q}} \sqrt{(1-x)(1-z)}$
    * $m_{ll} = m_{\tilde{q}} \sqrt{x(1-y)(1-z)}$
  - two parameters left: $f_q, x$
  - minimize $\chi^2$ in the $(x, f_q)$ parameter space
  - minimum $\chi^2$ when UED and SUSY masses are the same and $f_q \approx 1$

- 10% jet energy resolution + statistical error
  → $\chi^2$ better but not enough to fake SPS1a in UED
- effect of wrong jets → asymmetry smaller ? (work in progress)

\[ x = \left( \frac{m_{\tilde{q}0}}{m_{\tilde{q}}} \right)^2, \quad y = \left( \frac{m_{\tilde{\ell}}}{m_{\tilde{q}0}} \right)^2, \quad z = \left( \frac{m_{\tilde{\chi}^0_1}}{m_{\tilde{\ell}}} \right)^2, \quad f_q = \frac{N_q}{N_q+N_{\tilde{q}}}, \quad f_{\tilde{q}} = \frac{N_{\tilde{q}}}{N_q+N_{\tilde{q}}}, \quad f_q+f_{\tilde{q}} = 1 \]

- see Plehn and Wang’s talks for spins/ Nojiri, Gjelsten and Miller’s talks for masses
The Angular Distribution and Threshold Scans

(Battaglia, Datta, De Roeck, Kong, Matchev, hep-ph/0502041)

Mass determination

Cross section at threshold

\[ \beta = \sqrt{1 - \frac{M^2}{E_{\text{beam}}^2}} \]

\( \frac{\partial \sigma}{\partial \cos \theta} \) \( UED \) \( \sim 1 + \cos^2 \theta \)

\( \frac{\partial \sigma}{\partial \cos \theta} \) \( SUSY \) \( \sim 1 - \cos^2 \theta \)

\( \mu^+ \mu^- + \not{E}_T \) channel
The $\mu$ Energy Distribution and Photon Energy Distribution

(Battaglia, Datta, De Roeck, Kong, Matchev, hep-ph/0502041)

- $E_{max/min} = \frac{1}{2} M_{\mu^*} \left( 1 - \frac{M_N^2}{M_{\mu^*}^2} \right) \gamma(1 \pm \beta)$
  - $M_{\mu^*}$: mass of smuon or KK muon
  - $M_N$: LSP or LKP mass
- $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ with $\beta = \sqrt{1 - \frac{M_{\mu^*}^2}{E_{beam}^2}} (\mu^*$ boost)

- Smuon production is mediated by $\gamma$ and $Z$
- On-shell $Z_2 \rightarrow \mu_1 \bar{\mu}_1$ is allowed by phase space
- Radiative return due to $Z_2$ pole at

$$E_{\gamma} = \frac{s-M_{Z_2}^2}{2\sqrt{s}}$$
Summary

- LHC is finally coming

- New physics beyond the SM is expected to be discovered but will we know what it is?

- Many candidates for new physics have similar signatures at the LHC (SUSY, UEDs, T-parity).

- Universal Extra Dimensions
  - provide very interesting collider and dark matter phenomenology
  - Analogy to supersymmetry makes UEDs more interesting
  - Spin measurements at the LHC
Recent papers on UED

- Spin Measurements in Cascade Decays at the LHC, hep-ph/0605296, Wang, Yavin
- Distinguishing Spins in Decay Chains at the Large Hadron Collider, hep-ph/0605286, Athanasiou, Lester, Smillie, Webber
- Relic Abundance of dark matter in the minimal universal extra dimension model, hep-ph/0605280, Kakizaki, Matsumoto, Senami
- Precision electroweak constraints on Universal Extra Dimensions revisited, hep-ph/0605207, Gogoladze, Macesanu
- It’s a Gluino, hep-ph/0605118, Alves, Eboli, Plehn
- Dark matter in universal extra dimension models: gamma(KK) versus nu(R,KK), hep-ph/0604154, Hsieh, Mohapatra, Nasri
- Resonances from two universal extra dimensions, hep-ph/0601186, Burdman, Dobrescu, Ponton
- Measuring slepton spin at the LHC, hep-ph/0511115, Barr
- Is it SUSY?, hep-ph/0510204, Datta, Kane, Toharia .........
- SUSY can fit any signal excess and for every single process in SUSY, there is corresponding diagram in UED!
- In principle, SUSY and UED are different. Can we distinguish two models at the LHC?