Phenomenology of Bosonic Supersymmetry

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Outline

- What is the model? (BS)
  - MUEDs (Minimal Universal Extra Dimensions)
- Why is it interesting?
- What is the spectrum?
- What are the decays?
- How big are the cross-sections?
- How do we discover it at the Tevatron and the LHC?
- Can we tell it from SUSY?
- Cosmology of BS
  - Relic density
  - Direct detection
  - Indirect detection: neutrinos, positrons, photons.
Minimal Universal Extra Dimensions

- UEDs: everybody in the bulk!
  Appelquist, Cheng, Dobrescu hep-ph/0012100

- Motivation: EWSB, proton decay, \( N_{\text{gen}} \), neutrinos...
  Appelquist, Arkani-Hamed, Cheng, Dobrescu, Hall, Ponton, Poppitz, Yee

- The minimal model: \( d = 4 + 1 \), ED compactified on \( S^1/Z_2 \).

- Symmetries
  - \( Z_2 \) – project out unwanted zero modes
  - \textbf{KK number} – broken down to KK parity by boundary terms
    \((-1)^n\), for KK level \( n \Rightarrow \text{Lightest KK Particle} \) is stable

- Minimal UEDs: boundary terms vanish at a scale \( \Lambda > R^{-1} \)

- The model is very predictive: \( \{ R, \Lambda, m_h \} \)

- Current constraints exclude \( R^{-1} \lesssim 300 \text{ GeV} \).
Tree Level Mass Spectrum

- The tree-level spectrum is extremely degenerate:

\[ m_n^2 = \left( \frac{n}{R} \right)^2 + m_0^2 \]

- The radiative corrections are crucial for phenomenology, e.g.

\[ \epsilon_1 \rightarrow \gamma_1 \epsilon_0? \]

\[ m_{\epsilon_1} - (m_{\gamma_1} + m_{\epsilon_0}) \sim -R^{-1} \left( \frac{m_{\epsilon_1}}{R-1} \right) \sim -R^{-1} 10^{-6} \]
Radiative corrections

- Two types of corrections:
  - “bulk” – from loops with nonzero winding number
    \[ \delta m_n \sim R^{-1} \]
  - “boundary” – from boundary counterterms
    \[ \bar{\delta} m_n \sim m_n \ln \left( \frac{\Lambda^2}{\mu^2} \right) \]
Radiatively Corrected Mass Spectrum

- The radiative corrections split the spectrum $\Rightarrow$ prompt decays!

- LKP: KK “photon” $\Rightarrow$ missing energy!
- Hadron collider searches appear problematic – soft decay products.
The KK Weinberg Angle

- Mass matrix for the neutral gauge bosons

\[
\begin{pmatrix}
\frac{n^2}{R^2} + \frac{1}{4} g_1^2 v^2 + \hat{\delta}m_{B_n}^2 & \frac{1}{4} g_1 g_2 v^2 \\
\frac{1}{4} g_1 g_2 v^2 & \frac{n^2}{R^2} + \frac{1}{4} g_2^2 v^2 + \hat{\delta}m_{W_n}^2
\end{pmatrix}
\]

- The Weinberg angle $\theta_n$ at KK level $n$
  - At tree level: the same for all $n$
  - At one loop: decreasing with $n$, much smaller than $\theta_0$. 

![Graph showing $\sin^2 \theta_n$ vs. $1/R$ for different KK levels](image)
• KK gluon: \( B(g_1 \rightarrow Q_1 Q_0) \approx B(g_1 \rightarrow q_1 q_0) \approx 0.5 \).
• Singlet KK quarks \((q)\):
  \[
  B(q_1 \rightarrow Z_1 q_0) \approx \sin^2 \theta_1 \approx 10^{-2} - 10^{-3}
  \]
  \[
  B(q_1 \rightarrow \gamma_1 q_0) \approx \cos^2 \theta_1 \approx 1
  \]
• KK \(W\)- and \(Z\)-bosons: only leptonic decays!
  \[
  B(W_1^\pm \rightarrow \nu_1 L_0^\pm) = B(W_1^\pm \rightarrow L_1^\pm \nu_0) = 1/6
  \]
  \[
  B(Z_1 \rightarrow \nu_1 \nu_0) \approx B(Z_1 \rightarrow L_1^\pm L_0^\mp) \approx 1/6
  \]
• KK leptons: 100% directly to the LKP.
Level 1 Branching Fractions

- Doublet KK quarks ($Q$).

\[
B(Q_1 \rightarrow W_1^{\pm} Q_0) \approx 2B(Q_1 \rightarrow Z_1 Q_0) \\
\frac{B(Q_1 \rightarrow Z_1 Q_0)}{B(Q_1 \rightarrow \gamma_1 Q_0)} \approx \frac{g_2^2 T_{3Q}^2 (m_{Q_1}^2 - m_{Z_1}^2)}{g_1^2 Y_Q^2 (m_{Q_1}^2 - m_{\gamma_1}^2)}
\]

\[\text{R}^{-1} = 500 \text{ GeV}\]

- $Q_1 \rightarrow W_1^{+} Q_0$
- $Q_1 \rightarrow W_1^{-} Q_0$
- $Q_1 \rightarrow B_1^{0} Q_0$

\[
B(Q_1 \rightarrow W_1^{\pm} Q_0) \sim 65\% \\
B(Q_1 \rightarrow Z_1 Q_0) \sim 33\% \\
B(Q_1 \rightarrow \gamma_1 Q_0) \sim 2\%
\]

- We want: strong production, weak decays!
KK Production at the Tevatron

- The cross-section is quite significant
  
  Rizzo hep-ph/0106336
  Macesanu, McMullen, Nandi hep-ph/0201300

- $q_1$ production yields jets and $p_T$ - doable.
- $Q_1$ production yields leptons and $p_T$ - gold-plated.
Tevatron Search in $4\ell \not{E}_T$ Channel

- Arises from inclusive $Q_1Q_1$ production:
  \[ Q_1 \rightarrow Z_1 \rightarrow \ell^\pm \ell^\mp \gamma_1 \]

- Triggers
  - Single lepton $p_T(\ell) > 20$ GeV, $\eta(e) < 2.0$, $\eta(\mu) < 1.5$.
  - Missing energy $\not{E}_T > 40$ GeV.

- Cuts
  - $p_T(\ell) > \{15, 10, 10, 5\}$ GeV, $|\eta(\ell)| < 2.5$.
  - $\not{E}_T > 30$ GeV.
  - Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.

- Main background: $ZZ \rightarrow \ell^\pm \ell^\mp \tau^+ \tau^- \rightarrow 4\ell \not{E}_T$. Not a problem.
- $B(Q_1 \rightarrow 2\ell \not{E}_T + X) \sim \frac{1}{9}$. In principle, channels with $W_1$’s can also be used – less leptons, but more often.
• Humongous cross-sections at small $R^{-1}$.

![Graph showing the cross-section $\sigma$ in fb as a function of $M$ in GeV.]

• Cuts (pass the single lepton trigger)
  • $p_T(\ell) > \{35, 20, 15, 10\}$ GeV, $|\eta(\ell)| < 2.5$.
  • $\not{E}_T > 50$ GeV.
  • Invariant mass of OS, SF leptons: $|m_{\ell\ell} - M_Z| > 10$ GeV, $m_{\ell\ell} > 10$ GeV.
• Backgrounds: multi-boson, $ttZ$, fakes, etc.
Assumption: 50 events/year (100 fb$^{-1}$).
The reach in the $4\ell \not{E}_T$ channel. Require $5\sigma$ or 5 events.

- Other channels with larger statistics may give better reach (especially at the Tevatron).
- We did not optimize cuts.
UED or SUSY?

- Similarities between SUSY and the first KK level:
  - Superpartners versus KK modes
  - Couplings to SM particles
- Differences
  - Spins ("bosonic supersymmetry")
  - Absence of "Heavy Higgses" in MUEDs
  - No $D$-term splittings
  - Higher KK levels! Is this distinctive enough?
- How does a linear collider help?
• KK fermions: \( f_2 \rightarrow V_1 f_1 \) or \( f_2 \rightarrow V_2 f_0 \) (also \( f_2 \rightarrow f_2' W^\pm \)).
  Same for scalars. See level 1 KK searches.

• KK gauge bosons: \( V_2 \rightarrow f_1 \bar{f}_1 \), \( V_2 \rightarrow f_2 \bar{f}_0 \), but also \( V_2 \rightarrow f_0 \bar{f}_0 \).

• KK2 pair production + KK number violating decays \( \Rightarrow \)
  dilepton/dijet bumps at high inv. mass + large \( E_T \) + soft stuff.

• KK2 single production + KK number violating decays \( \Rightarrow \)
  similar to \( Z', W' \) searches.
• Relic density: G.Servant, T.Tait hep-ph/0206071

\[ \Omega h^2 = \frac{1.04 \times 10^9 \text{ GeV}^{-1}}{M_P \sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \quad x_F = \frac{M_{KK}}{T_F} \]

\[ a = \frac{\alpha_1^2}{M_{KK}^2} \frac{380\pi}{81}; \quad b = -\frac{\alpha_1^2}{M_{KK}^2} \frac{95\pi}{162}. \]

• Unlike supersymmetry: coannihilation lowers the bound
KK dark matter detection

- Direct detection: promising. (Similar to SUSY models with small sfermion–LSP mass splitting.)
- Indirect detection
  - Positrons: promising. Narrow peak at large $E_{e^+}$.
  - Photons: similar to SUSY.
- Can DM experiments help in determining the LKP spin?
Conclusions and Outlook

- MUEDs are a complete and calculable model of ED.
- The LKP is neutral and stable $\Rightarrow$ the generic collider signature of MUEDs is $E_T$.
- The LHC can probe $R^{-1}$ up to $\sim 1.5$ TeV in multilepton channels. Other channels? Beyond MUEDs?
- KK level 1 of MUEDs looks just like supersymmetry!
  - How do we tell the difference? (challenge for Tevatron and LHC experimentalists...)
  - Can we make sense of KK level 2 if we see it?
- The role of a linear collider in all of this?
- A 1 TeV LKP is a good dark matter candidate and offers very good opportunities for detection.