The Complete Phase Diagram of Minimal Universal Extra Dimensions

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Motivations

• **Naturalness**
  – String landscape, inflation
  – Little hierarchy – is 5% fine-tuning too much?
  – Good time to diversify

• **Cosmology**
  – Incontrovertible progress
  – Dark matter is the best evidence for new physics (beyond Higgs) at the weak scale. Theoretically attractive, implications for central problems
  – Room for ideas, even after 100 s

• **LHC**
  – Exotic signatures: are signals being lost in triggers, analyses?
  – Spectacular signals may be found in first 2 years, should be explored now
Preview

• Consider minimal Universal Extra Dimensions, a simple, 1 parameter extension of the standard model
  
  – Unnatural, but dark matter $\rightarrow$ weak scale
  
  – Diverse cosmological connections
  
  – Many exotic signatures for the LHC
Universal Extra Dimensions

• Following Kaluza and Klein, consider 1 extra dimension, with 5\textsuperscript{th} dimension compactified on circle $S^1$ of radius $R$

• Put all fields in the extra dimension, so each known particle has a KK partner with mass $\sim nR^{-1}$ at level $n$

• Problem: many extra 4D fields; most are massive, but some are massless. E.g., 5D gauge field:

\[
V_\mu(x^\mu, y) = V_\mu(x^\mu) + \sum_n V_\mu^n (x^\mu) \cos(ny/R) + \sum_m V_\mu^m (x^\mu) \sin(my/R) \\
V_5(x^\mu, y) = V_5(x^\mu) + \sum_n V_5^n (x^\mu) \cos(ny/R) + \sum_m V_5^m (x^\mu) \sin(my/R)
\]
• Solution: compactify on $S^1/Z_2$ interval (orbifold); require
\[ y \to -y : \quad V_\mu \to V_\mu \quad V_5 \to -V_5 \]

• Unwanted scalar is projected out:
\[
\begin{align*}
V_\mu(x^\mu, y) &= V_\mu(x^\mu) + \sum_n V^n_\mu(x^\mu) \cos(ny/R) + \sum_m V^m_\mu(x^\mu) \sin(my/R) \\
V_5(x^\mu, y) &= V_5(x^\mu) + \sum_n V^n_5(x^\mu) \cos(ny/R) + \sum_m V^m_5(x^\mu) \sin(my/R)
\end{align*}
\]

• Similar projection on fermions $\to$ 4D chiral theory at $n = 0$ level

• $n=0$ is standard model [+ gravi-scalar]

• Very simple, assuming UV completion at $\Lambda \gg R^{-1}$

Appelquist, Cheng, Dobrescu (2001)
KK-Parity

- An immediate consequence: conserved KK-parity \((-1)^{KK}\)
  Interactions require an even number of odd KK modes

  - 1\textsuperscript{st} KK modes must be pair-produced at colliders

  - Weak bounds: \(R^{-1} > 250\) GeV

  - LKP (lightest KK particle) is stable – dark matter
Minimal UED

• In fact, can place mass terms on the orbifold boundaries

• These would typically break KK-parity (eliminate dark matter), or introduce flavor- and CP-violating problems

• Here assume these are absent – this defines minimal UED

• mUED is an extremely simple, viable extension of the SM: 1 new parameter, $R$
Mineral UED KK Spectrum

Cheng, Matchev, Schmaltz (2002)
mUED Common Lore

• mUED looks like SUSY
  – $n=2$ and higher levels typically out of reach
  – $n=1$ Higgses $\rightarrow A, H^0, H^\pm$
  – Colored particles are heavier than uncolored ones
  – LKP is stable $B^1 \rightarrow$ missing energy at LHC

• Spectrum is more degenerate, but basically similar to SUSY

  “Bosonic supersymmetry”

  Cheng, Matchev, Schmaltz (2002)
$B^1$ Dark Matter

- Relic density:
  Annihilation through

Similar to neutralinos, but higher masses preferred

\[ \Omega h^2 = 0.16 \pm 0.4 \]

Servant, Tait (2002)
B1 Dark Matter Detection

Cheng, Feng, Matchev (2002)

- **Direct Detection**
  *e.g.,* $B^1 q \rightarrow q^1 \rightarrow B^1 q$

- **Indirect Detection**
  *e.g.,* $B^1 B^1 \rightarrow e^+ e^-$

Some interesting differences relative to neutralinos, but basically WIMP-like
But Wait, There’s More

- $R$ is the only new parameter, but it is not the only free parameter: the Higgs boson mass is unknown

- These studies set $m_h = 120$ GeV, but it can be larger

- $H^0$, $A$, $H^\pm$ masses depend on $m_h$

Appelquist, Yee (2002)
The KK Graviton

• The KK graviton $G^1$ exists with mass $R^{-1}$ and can be lighter than the $B^1$

• $(B^1, W^1)$ mass matrix:

$$
\begin{pmatrix}
R^{-2} + \frac{1}{4}g^2 v^2 + \delta m_{B^1}^2 & \frac{1}{4}g'g v^2 \\
\frac{1}{4}g'g v^2 & R^{-2} + \frac{1}{4}g'^2 v^2 + \delta m_{W^1}^2
\end{pmatrix}
$$

$$
\delta m_{B^1}^2 = \left( -\frac{39}{2} \frac{g^2 \zeta(3)}{16\pi^4} - \frac{g^2 \ln(\Lambda^2 R^2)}{6} \frac{16\pi^2}{16\pi^2} \right) R^{-2}
$$

$$
\delta m_{W^1}^2 = \left( -\frac{5}{2} \frac{g^2 \zeta(3)}{16\pi^4} + \frac{15g^2 \ln(\Lambda^2 R^2)}{2} \frac{16\pi^2}{16\pi^2} \right) R^{-2}
$$
Complete Phase Diagram

- Including the graviton, there are 6 (NLKP, LKP) phases.

- The triple point with \(G^1, B^1, H^\pm\) all degenerate lies in the heart of parameter space.
Collider Phase Diagram

• To make progress, first exclude $G^1$
  – Decouples cosmology
  – Reduces complexity

• Then there are 4 (NLKP, LKP) phases

• Note: $m_h=120$ GeV lies entirely in Phase 1
Degeneracies

- The lightest states are extremely degenerate
- One might expect degeneracies of $m_w^2 R^{-1} \sim 10 \text{ GeV}$
- Modest accidental cancelations tighten the degeneracies
• This leads to long decay lengths: microns to 10 m

\[
\Gamma(H^{\pm} \to B^{1} f \bar{f}') = \frac{N_C g^2 g'^2}{49152 \pi^3} \frac{M^5}{m_W^3 m_1^2} \times \\
\left( (1 - y) (1 + y + 73y^2 + 9y^3) + 12y^2 (3 + 4y) \ln y \right) \\
\approx \frac{N_C \alpha^2}{80 \pi \sin^2 \theta_W \cos^2 \theta_W} \frac{(\Delta m)^5}{m_W^3 M^2} \\
\approx 1.96 \times 10^{-16} \text{ GeV} \frac{\Delta m}{\text{GeV}} \left[ \frac{\text{GeV}}{M} \right]^5 \left[ \frac{\text{TeV}}{M} \right]^2 \\
\approx \left[ 1.01 \text{ m} \frac{1}{N_C} \frac{1}{\Delta m} \frac{1}{\frac{\text{GeV}}{M}} \frac{1}{\left[ \frac{\text{M}}{\text{TeV}} \right]^2} \right]^{-1},
\]
LHC Signals

- Kinks: \( H^\pm \rightarrow B^1 e \nu \)
- Displaced vertices: \( H^\pm \rightarrow B^1 u d \)
- Vanishing tracks: \( H^\pm \rightarrow B^1 (e) \nu \)
- Highly-ionizing tracks: \( H^\pm \)
- Time-of-flight anomalies: \( H^\pm \)
- Appearing tracks: \( A \rightarrow H^\pm (e^\pm) \nu \)

- Appearing tracks: \( A \rightarrow H^\pm (e^\pm) \nu \)
- Impact parameter: \( A \rightarrow H^\pm (e^\pm) \nu \)
- …
- Decays in vertex detectors, trackers, calorimeters, muon chambers, outside detector are all possible.
Cosmological Phase Diagram

• Can cosmological constraints restore order?

• Include $G^1$ – cosmologically relevant when it’s the LKP

$[H^\pm \rightarrow G^1 \text{ takes } 10^{26} \text{ s}]$
Charged Stable Relics

- Charged stable relics create anomalously heavy isotopes
- Severe bounds from sea water searches
- But inflation can dilute this away
- What is the maximal reheat temperature?

Masses $< \text{TeV}$ are excluded by $T_{RH} > 1 \text{ MeV}$, but masses $> \text{TeV}$ are allowed

Kudo, Yamaguchi (2001)
Diffuse Photon Flux

- Late $B^1 \rightarrow \gamma G^1$ contributes to diffuse photon flux.

- Small $\Delta m$ implies smaller initial energy, but also less red shifting; latter effect dominates.

- Excludes lifetimes $< 10$ Gyr, but again evaded for low $T_{RH}$.

\[ (d\phi/dE_\gamma)^{obs} = \alpha(E/E_0)^{-\delta} \]  
\[ E_\gamma \text{ (MeV)} \]  
\[ d\phi/dE_\gamma \text{ (MeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1}) \]

Feng, Rajaraman, Takayama (2003)
Overproduction of $B^1$ WIMPs

• The original calculation of thermal relic densities has now been greatly refined
  – Radiative contributions to masses included
  – $n=2$ resonances included
  – All co-annihilations included

  Kakizaki, Matsumoto, Sato, Senami (2005); Burnell, Kribs (2005)
  Kong, Matchev (2005); Kakizaki, Matsumoto, Senami (2006)

• The requirement that $B^1$’s not overclose the universe also restricts the parameter space (but is again avoided for low $T_{RH}$)
Complete Cosmologically Constrained Phase Diagram

- Assuming $T_{RH} > 10$ GeV, get triangle region, predict
  - Long-lived tracks at colliders
  - $180$ GeV < $m_h$ < $245$ GeV
  - $R^{-1} > 800$ GeV
  - All KK masses degenerate to 330 GeV
  - $B^1 \rightarrow G^1$ may be happening right now

- This is not like SUSY
CONCLUSIONS

• mUED is a simple, 1 parameter extension of the SM

• Nevertheless it has extremely rich implications for particle physics and cosmology

• “Exotic” signatures may produce spectacular signals soon if we are prepared; much work to be done