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 5th 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:

\[
V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu) \cos(ny/R) + \sum_m V_\mu^m(x^\mu) \sin(my/R)
\]

\[
V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu) \cos(ny/R) + \sum_m V_5^m(x^\mu) \sin(my/R)
\]
• Solution: compactify on $S^1/Z_2$ interval (orbifold); require

$$y \rightarrow -y : \quad V_\mu \rightarrow V_\mu \quad V_5 \rightarrow -V_5$$

• Unwanted scalar is projected out:

$$V_\mu(x^\mu, y) = \underbrace{V_\mu(x^\mu)}_{\text{good}} + \sum_n V_\mu^n(x^\mu) \cos(ny/R) + \sum_m V_\mu^m(x^\mu) \sin(ny/R)$$

$$V_5(x^\mu, y) = \underbrace{V_5(x^\mu)}_{\text{bad}} + \sum_n V_5^n(x^\mu) \cos(ny/R) + \sum_m V_5^m(x^\mu) \sin(ny/R)$$

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

• $n=0$ is standard model [$+\text{gravi-scalar}$]

• 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

- $1^{\text{st}}$ 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, $R$
Minimal 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
  \[ B^1 q \rightarrow q^1 \rightarrow B^1 q \]

- Indirect Detection
  \[ B^1 B^1 \rightarrow e^+ e^- \]

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:

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

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

$$
\delta m^2_{W^1} = \left( \frac{5 g^2 \zeta(3)}{2 \ 16\pi^4} + \frac{15 g^2 \ln(\Lambda^2 R^2)}{2 \ 16\pi^2} \right) R^{-2}
$$
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
NLKP Decays

- This leads to long decay lengths: microns to 10 m

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

$[H^\pm \rightarrow G^1$ takes $10^{26}$ 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 < TeV are excluded by \( T_{RH} > 1 \text{ MeV} \), but masses > TeV are allowed
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 $T_{RH}$.
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 $T_{\text{RH}} > 10 \text{ GeV}$, get triangle region, predict
  – Long-lived tracks at colliders
  – $180 \text{ GeV} < m_h < 245 \text{ GeV}$
  – $R^{-1} > 800 \text{ GeV}$
  – 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